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Research Paper

Structural Health Monitoring of Steel Girder Bridge Using Photogrammetry and LiDAR Scan Technology: Proof of Concept

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ABSTRACT

Bridges require regular inspection and maintenance; however, traditional inspections are performed manually at prescribed intervals, involving substantial manpower, high costs, and safety risks due to the challenging locations of many bridges. To address these limitations, the present study focused on developing a methodology to automate technical inspections of bridges using a hybrid approach combining LiDAR and photogrammetry. Unlike past drone inspections, which were largely limited to basic photography and videography, this approach integrates advanced technologies for more comprehensive data collection. For this purpose, a single-span steel girder bridge with a span of 45.7 meters, located between Beas and tto Tanda in the state of Punjab, India, was selected. A Proof-of-Concept (PoC) was developed using high-fidelity digital models, created through photogrammetry with UAV-mounted high-resolution cameras and LiDAR, to carry out 16 inspection missions. The development of these high-fidelity digital models enabled flexible viewing, analysis, and measurement of various structural parameters, including the schedule of dimensions diagram, camber, distortions, rail levels, creep, and eccentricity. The parameters measured from the digital models were compared with the limiting values specified by RDSO, as well as with manually collected data. It was observed that the dimensional measurements obtained through the automated technology were within ± 5 mm of the drawings and previous inspection reports, indicating that photogrammetry combined with LiDAR is a reliable and effective alternative technology for bridge inspection.

1 Introduction

There are more than 150000 bridges in Indian railways including 700 important and 1200 major bridges. These bridges require regular inspection and maintenance. Inspection of these bridges is performed manually as per prescribed periodicity. Manual inspection of bridges involves substantial manpower, cost and entails danger due to the location of bridges. Further,

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inspecting bridges manually also takes considerable time. Hence, conventional method of bridge inspection is a cumbersome, labour intensive, time-consuming and expensive process. Dederichs et al., [1] proposed a new novelty detection algorithm intended to work with missing and randomly available natural frequency information. It was concluded that the performance of the novelty detection algorithm is not expected to match state-of-the-art damage detectors, however its performance is shown to be more than satisfactory on two numerical cases, and two experimental bridges. Azhar et al. [2] carried out comprehensive review on structural health monitoring of the bridges and stated that the future of vibration-based methods is potentially tremendous as a structure characterization solution as it provides the state-of-the-art data-driven measures towards damage detection. Bai et al. [3] proposed a new framework for monitoring the dynamic performance of bridges using three different cameras and a few visual data processing techniques along with the deep learning method. It was concluded that the vibrations and frequencies of structures able to capture accurately with the proposed framework and the camera placements and data processing techniques can be successfully used for monitoring their dynamic performance. Deng et al. [4] observed that SDI methods are based on structural vibration effects. However, non-destructive testing performs well in assessing the damage and is suggested to be further developed and applied in the future. It was also observed that no universally applicable method for Level 4 SDI. Hao et al. [5] introduced a low-power Internet of Things method to detect bridge displacement in wireless sensor systems. This system can greatly reduce the limit of the transmission distance, accurately collect displacement data, and send it to the server for remote analysis and visual operation via a web interface. Based on the experimental and field test results, the effectiveness of the system was verified. He et al. [6] concluded that the challenges faced by the current bridge system from five perspectives such as technology, environment, economy, safety, and security. Also, it was suggested that the popularization of more innovative technologies elevates the health monitoring of bridges to a new level. Li et al. [7] developed a bridge health monitoring system through the combination of building information modeling and traditional bridge health monitoring able to organize and visualize a considerable amount of sensor data and subsequent structural health information over a prolonged period. It was concluded that the developed system was capable of judging the damage of the structure. Svendsen et al. [8] applied an unsupervised machine learning algorithm and compared it with four supervised machine learning algorithms and it was observed that the damage types that can best be detected are performed by utilizing the supervised machine learning algorithms.

Lim et al. [9] proposed a measurement system for the vibration characteristics of suspension bridges based on low-frequency cantilever-based fiber Bragg grating accelerometers (CFAs) and verified the accuracy of the system on a suspension bridge in Malaysia. Additionally, the system can trigger early damage warnings when detecting changes in vibration characteristics. Piervincenzo and Alireza [10] observed based on the comprehensive literature review that it is difficult to design a uniform health monitoring paradigm as any bridge bridges, little is common with each other, and every new bridge is unique. Therefore, it was concluded that complication increases when the structures are modeled, and damage can only be simulated numerically but not (logically) induced experimentally. Zhang et al. [11] proposed a fully automated and robust method based on the xnode wireless sensor system. The method revealed that that natural frequency and order of the bridge cable obtained by this method and the Matlab method found consistent. Further, it was also concluded that the predicted tension results matched the actual data well and can effectively realize the automatic estimation of cable tension. BS-129 [12] proposed technical matters regarding usage of drone inspection and covers visual aspects of bridge inspection. However, there are other aspects such as automated technology that do not form part of the report. Ayyildiz et al. [13] developed sensor mote hardware is based on the lead zirconate titanate material, which had excellent fracture detection performance. They used the network interface to remotely analyse the data collected from the piezoelectric sensor. It was observed that the newly developed system able to successfully detect the cracks in the structures. Zhao et al. [14] studied the early warning method of deflection change in railway bridges caused by temperature and train load. They used the monitoring data and the mutual update of the train–bridge dynamic model to monitor the bridge deflection behavior and, at the same time, determined the early warning threshold of it under the combined action of the two factors. Chen et al. [15] proposed a foundation scour evaluation method based on the ambient vibration measurement of the local pier frequencies on the cable-stayed bridge. Further, FE model based on the original design parameters was developed. Based on the measured and model results, it was observed that the best support boundary conditions were identified as well as the optimal soil stiffness. It was concluded that the local pier scour depth is estimated by changing the depth of the soil to fit the local frequencies. Sloane et al. [16] proposed a strategy to monitor the eventual corrosion of the high-strength steel wires of suspension bridges which are based on a sensor network that assesses indirectly the environmental conditions and deterioration of the main cables. It was observed that the tested sensor network is able to provide suitable clues about the interior environment of the cable. Bazant et al. [17] investigated excessive deflections of Koror-Babeldaob Bridge in Palau. The measured results were compared with the models such as American Concrete Institute 1992 [18], B3 model [Bazant and Baweja [19] and Bazant

and Prasannan [20]], CEB-FIP Model Code[21] and GL model 2000 [22]. It was observed that most of the models underestimated the deflections, however, model B3 seemed to be the best because the multiple calibrated independent material parameters could fit the measured deflection well by linear regression scaling. Kwon and Frangopol [23] applied concepts related to fatigue reliability to the Neville Island Bridge and the Birmingham Bridge, both in the city of Pittsburgh, Pennsylvania. Further, the rainflow counting method was used to obtain the stress-range bin histogram from the monitoring data. It was concluded that there were seven steps involved in total to conduct the assessment of the bridges. Guo et al. [24] proposed an approach to evaluate the time-dependent fatigue reliability of steel bridges with traffic load model and probabilistic finite element analysis. Yun et al. [25] investigated the effect of collision of a cargo ship with the Vincent Bridge in Los Angeles in order to evaluate the structural condition of the bridge before and after collision. The condition of bridges was evaluated using multi-sensor identification approaches based on the Natural Excitation Technique in conjunction with the Eigensystem Realization Algorithm. It was concluded that approaches served well to extract the modal characteristics of the bridge. Meo and Zumpano [26] developed two comparative standards using vibration displacement as the dataset. The first standard is the mean square error between the FE model and the cubic spline-interpolated mode shapes, and the second standard is the information content of the sensors, which shows the signal strength obtained by different placement schemes and their noise resistance ability. Ghali et al. [27] investigated both short term and long-term behavior and performance of the Confederation Bridge in Canada. Also, the time-dependent properties of concrete were predicted and compared with the deflections measured in the field. Overall, it was observed that the predicted results found to match well with the measured results. Catastrophic failures also harmed public safety and cause worst case scenarios, and the collapse of Silver Bridge killed 46 innocent lives in 1976, Harik et al. [28] and Lichtenstein [29] while the failure of Quebec Bridge killed 75 people during its construction, Pearson and Delatte [30]. This accident changed the nation's view of bridges across the country and the government changed the way bridges were inspected to ensure safety and functionality. There are different methodologies such as vibration-based damage Detection approach, statistical approaches and signal processing techniques have also been studied by Rahami et al. [31] and Wang and Chan [32].

Based on detailed literature, it was observed that the application of automated technology in bridge inspection was found limited. Hence, it was proposed to build upon the RDSO guidelines and arrive at specifications and methodology to automate technical inspections of bridges with the aim to supplant manual technical inspections. Drone inspection performed in the past has been limited to photography and videography of the structure, however a mixed approach of photogrammetry and LiDAR combined with engineering solutions were proposed. Although the principles applied and technology used are established, their application to the field of railway bridges is not widespread. Therefore, advancement of UAV (Drone) based photogrammetry and LiDAR technology has developed a possibility to adopt indirect inspection techniques in the digital environment for railway bridges in the present study, see Section 2. Further, a Proof of Concept was planned to validate the parameters such as schedule of dimensions diagram, camber measurements, distortions, rail levels, creep measurement and eccentricity, see Section 3. Lastly, to explore the possibilities of analysis and findings were concluded in Section 4. Also, the future development of the present study is discussed in Section 5.

2 Illustrations

2.1 Proof of concept

A single span steel girder bridge (1 x 45.7m) was considered and the bridge is located on BEAS-TTO in the state of Punjab, India. A single span electrified track open web bridge was selected since BEAS-TTO line is a branch line having less traffic which was suited for the present work, see Fig. 1. Steel girder bridges are a complex lattice structure and inspection of these bridges require both visual assessment and precise dimensional measurement to check deformation or degradation of bridge to undertake preventive or corrective maintenance well in advance. In order to inspect the health of the bridges, the Proof-of-Concept (PoC) was developed using automated technology such as photogrammetry by UAV mounted high resolution cameras and LiDAR. The drone imagery approach alone is not enough, therefore, LiDAR technology needs to be brought for sub-centimeter measurements. Both UAV assisted imagery and LiDAR technology were deployed to leverage advantages of both technologies. The UAV mounted high resolution cameras were used to capture RGB imagery from all possible directions including under the bridge by mounting cameras on top of drone. The optical zoom camera was used for close-up photographs of critical elements of the bridge, a technique often used in wind turbines. In addition to drone mounted cameras, using terrestrial LiDAR scanner, the entire bridge was scanned from multiple locations. The approach used in the proof of concept were compared with the RDSO guidelines, see Table 1.



Fig. 1 - Highest resolution google map image of bridge.

Table 1 - Comparison of RDSO guidelines and proof of concept in the present study.

Area	RDSO Guidelines	Approach used in the Proof of concept
Methodology	UAV (Drone) and camera to capture photos and video of inaccessible areas of bridge.	– Drones along with higher resolution camera with downward and upward gimble are flown in autopilot preplanned routes. – Additionally, terrestrial LiDAR was used. – A 30x optical zoom camera was also used for better clarity of CAPI.
Survey /Data Capture Processes	RDSO guidelines generally cover how to operate the drone however misses out specifics necessary for consistency, repeatability, and totality. Some of the parameters specified in RDSO guidelines seemingly not tested in field.	– A very comprehensive time-tested workflow is adopted based on Drones' experience in Australia which includes a step-by-step process to reduce dependency on pilot skills and local decision making. – This process is scalable and can be adopted to produce consistent outcomes in any bridge.
Raw Output	Photos and video	– Point cloud and high-resolution geo tagged imagery.
Desired output	4K quality video with geotagged file and photographs and surface model	– Photorealistic and dimensionally accurate 3D model generated from point cloud which has far more details than DSM.
Software	Photoscan	– Bentley system's Context capture and Autodesk's ReCAP for desktop-based processing and Pix4D /Drone Deploy for quick cloud-based processing and visualization. – Context capture viewer (free) for viewing with interactivity.
Results	Photos, videos and approximate 3D reality model for visual inspection.	– A high-fidelity 3D model which is accurate to take measurements of all schedules of dimensions including complex measurements such as camber and distortion, bearing heights, L-section etc.

The scope of proof-of-concept was to prove that a geometrically accurate 3D model of the bridge may be built from drone based aerial imagery aided by data captured from terrestrial LiDAR sensors, to conduct virtual visual inspection from 3D model and measure various dimensions to ensure integrity of bridge and conformity with normal.

With UAV assisted imagery large areas may be covered in a short period with high relative accuracies in x and y axis and high-resolution images enable visually inspect the bridge. LiDAR's image resolution is nominal, however the point cloud has very high relative positional accuracy, which is necessary for measurements. Geo-reference photos taken from UAV mounted high-resolution CMOS sensors with an overlap (<75%) were merged and orthorectified using photogrammetry software to build uniformly scaled single orthophoto and photorealistic 3D surface models. Similarly, LiDAR scanner gathered accurate, complete, and photorealistic point clouds of the bridge's surface by determining distance with a laser and measuring the time for the reflected light to return to the receiver. The point cloud gathered from multiple scans from various sides of the bridge was merged to build a digital 3D replica of the bridge. The activities involved in the proof of concept are shown in Table 2.

Table 2 - Activities involved in the proof of concept.

Plan	Capture	Analyse and report
Mission planning	Execution	Closure
Desktop study of the site	Pre-flight checks and procedure	Data download
Type of bridge	Check weather	Remove SD Card from RPA and store
Height, width and length of bridge	Travel to site	Transfer data to computer
Key features to be captured (Piers, girders)	Assess site and airspace for safe flying	Upload on cloud/courier memory stick to client
Mark area of interest on side and plan view	Deploy appropriate signage	Email to client
Location details (Access)	Go through the check list and confirm	Analysis
Job safety assessment	Setup equipment	Process data to agreed scope
Key threats, Hazards and risks	Pilot to brief spotter or other personnel	Compare data with other information
Controls and measures	Tune Aviation radio to monitor airspace	Report
Identify possible take-off and landing spot	Fly and capture images	Generate summary report
Check civil aviation - NOTAM	Take off	Sharing data with client
Check weather forecast	Capture images as planned	Documentation
Fill checklist	Capture video footage from 2 altitudes	Report incidents (if any)
Approvals and authorizations	Capture top view of tower	Fill log book in drone compiler
Chief pilot authorization	Land	Close the job in drone compiler

Table 2 (continued) - Activities involved in the proof of concept.

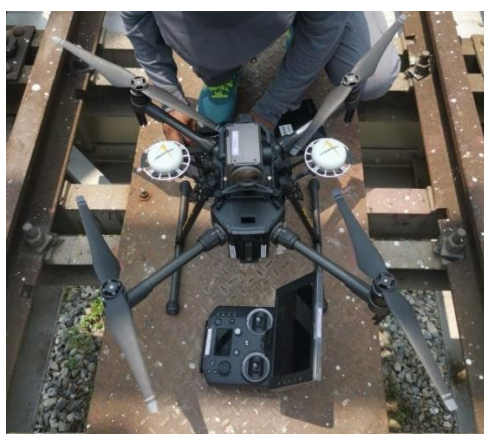
Plan	Capture	Analyse and report
Railways approvals (as necessary)	Check results and repeat if necessary	Update lessen learnt doc
Scheduling		Feedback Loop
Job allocation to remote pilot	Carry out post flight check as operating manual	Ask for feedback of client
Job allocation to spotter		Implement improvements
Equipment	Travel back to office	
Allocated and block equipment to be used		
Software update as necessary		
Calculate and charge batteries needed		
Memory (SD Card-space check)		

Further, the weather plays a major role in any manual health monitoring and affects the accuracy and timelines, however the impact of weather on UAV and LiDAR Survey is minimal as it requires smaller time window to complete the survey. Several iterations over a two days period were performed, however one iteration can be completed in 3 to 4 hours assuming LIDAR and UAV teams operate in parallel. The weather on the day of data capture was humid (85%) and the temperature was more than 35° C during the day with occasional showers forecasted. The wind speed was around 15 km per hour during the day. The lighting condition on the day of the survey was moderate with overcast clouds between 8:00 am to 5:00 pm.

2.2 Equipment selection

2.2.1 UAV / Drone

The drones M210 quadcopter with RTK was chosen as the primary UAV. The platform DJI M210 is versatile and compatible with multiple DJI's was considered, Fig. 2(a-b). In addition to standard downward camera mounting gimbal, upward camera mounted gimbal was used to take under the bridge photographs.



(a)



(b)



(c)

Fig. 2 – (a) DJI M210 RTK with Z30 camera (b) RTK base station and (c) DJI Zemmuse 30 camera.

2.2.2 Sensors

The RGB sensors (X5S and Z30) of two numbers were chosen for the present study. The X5S is fitted with 4/3 inches CMOS sensors with effective 20.8 mega pixels. This was the primary sensor for capturing high resolution RGB imagery. The DJI Z30 has 1/2.8 inch CMOS 2.13 mega pixels sensor, see Fig. 2(c). However, this camera has 30x optical zoom which makes it best in class of aerial inspections. This camera has tap and zoom functionality which allows tapping on screen to zoom-in to the area of interest. This camera also features burst mode to take multiple photographs in a short period of time, useful for moving objects.

2.2.3 LiDAR

The Terrestrial Faro s 350 scanner was used as LiDAR scanner and scanner capable of capturing up to 2 million data points in one second at a distance 153 meters. Manufacturers of Faro scanner claim its ranging error is 1 mm up to distance of 25m and beyond 25m, it has 0.1mm/m of uncertainty. By virtue of experience, the Faro s 350 LiDAR scanner end results involving multiple scans are accurate in the range of +/- 5mm in most cases.

2.3 Mission

A significant amount of time was spent in the development of PoC prior to mobilization of staff and equipment to the field. A step-by-step instruction was prepared outlining exact activity to be performed by drone operator and field staff. Bridge blueprints / drawings were studied and analyzed as part of planning exercise prior to mobilizing staff and equipment to the site. A job safety assessment (JSA) was carried out to identify safety hazards to people, equipment and / or rail operations and any necessary mitigation actions were put in place to eliminate or minimize the risks or hazards. Power or traffic block was not taken; however constant communication was maintained with nearest station for any train movement. The UAV flights were kept below 50m above ground level (AGL) hence civil aviation approvals were not required. The entire health monitoring study was performed as 16 missions, see Fig. 3. The first 13 missions involved flying UAV with RGB sensors and 14-15 missions were ground based data capture and the 16 mission is last mission was terrestrial LiDAR involving 37 passes. There are 13 UAV missions that were pre-programmed using Pix4Dcapture software prior to going to the site, see Fig. 4(a). Minor adjustments were made by the UAV pilot at the site to suit local conditions, whereas the LiDAR passes were determined on at the site, see Fig. 4(b). The actual spatial representation of sensor positions of UAV is shown in Fig. 4(c) and 2,200 photographs and 16 gigabytes of LiDAR data were gathered from all 16 missions. The georeferenced photographs of about 2200 were taken from 13 missions and over 200 photos are taken from Z30 camera, see Fig. 4(d). The vertical and horizontal overlap 80% was maintained to achieve high quality 3D model. The UAV was flown at speed of 5km/hour at an altitude of 15 meters higher than bridge height.

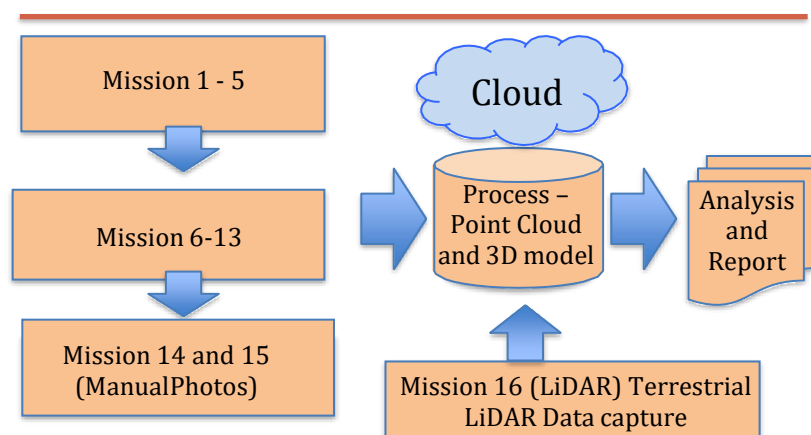
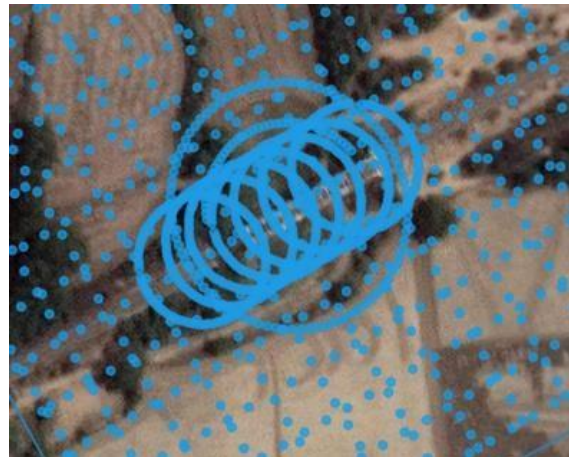
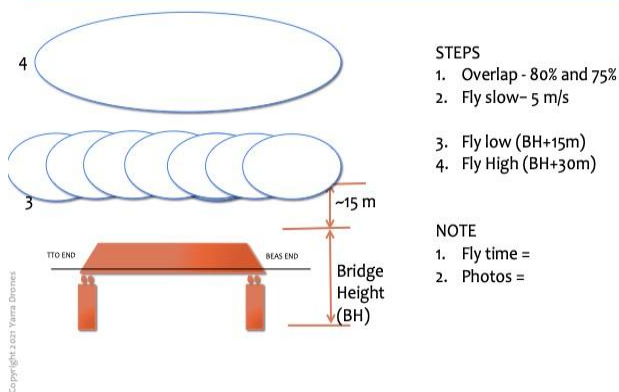


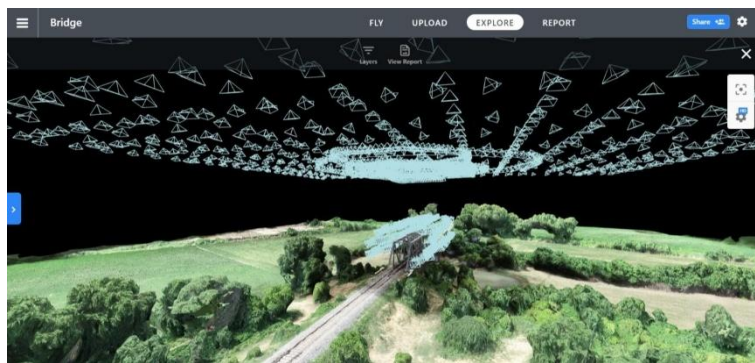
Fig. 3 - Mission flow chart.

Mission 2 – 3D (Pol- Vertical)



(a)

(b)



(c)



(d)

Fig. 4 - (a) proposed and (b) actual flight path along with (c) sensor position spatial locations and (d) typical georeferenced photographs.

3 Results and Discussion

The development of high-fidelity digital models of a bridge lead to flexibility in viewing, analyzing and measuring different parameters such as schedule of dimensions diagram, camber measurements, distortions, rail levels, creep measurement and eccentricity, see Section 3.1 to 3.6 and aspects that are not available in case of manual inspections at site, see Section 3.7.

The digital models were extracted from the photogrammetry 3D model as well as LiDAR point cloud images are shown in Fig. 5(a-b). The digital model can be rotated to view from different angles – elevation, plan, end view, isometric and anything in between; areas of interest can be zoomed in to take a close view and can be zoomed out to gain perspective. Cross sections can be taken at any place to gain novel insights. In the case of manual inspections, there is no option to review data; and doing revisions, if at all, are only possible by going back to the site and doing it all over again. Whereas, in the case of a

digital method, the results can be reviewed and corrected without the need to go back to the site. Once the parameters are measured and noted, they can be analysed (either by comparing them to absolute values or statistical variations over months or years). In case of deviations, further engineering studies can be commissioned to find out the root cause and corrective actions planned.

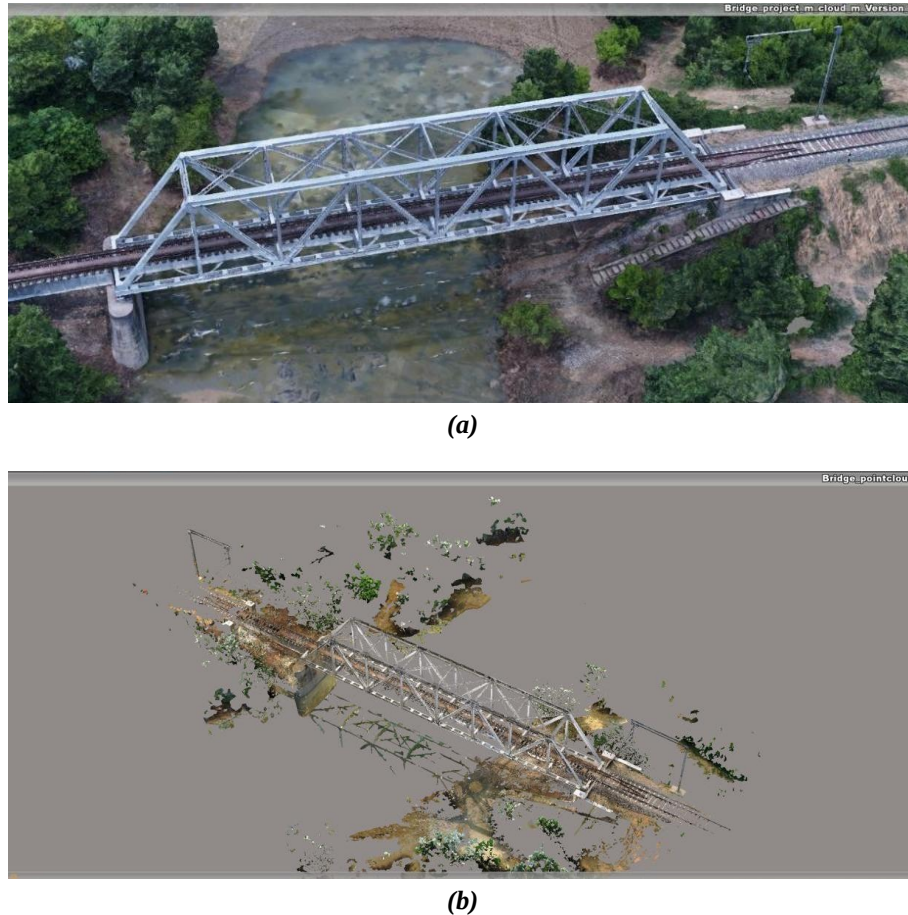


Fig. 5 - (a) Post processed photogrammetry 3D model and (b) LiDAR point cloud of bridge.

3.1 Schedule of Dimensions

It is essential to ensure safety of traveling public as well as goods over entire Indian railway system. Therefore, the schedule of dimensions is an essential measurement of clearances, however, it includes major dimensions of the bridge. These dimensions have been taken from two views – elevation of the bridge giving the length, clear span and cross-sectional view that gives the gauge and clearances. The schedule of dimensions at elevation were laid down with limiting values as per RDSO, manually measured data and predicted data from digital models are shown in Table 3.

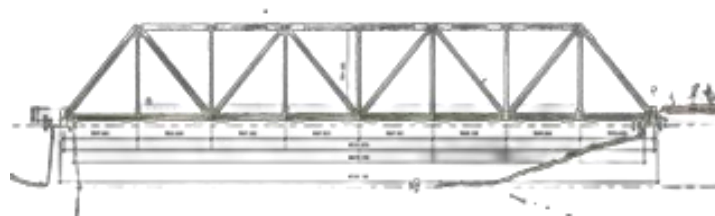
The typical schedule of the dimension diagram of elevation view is shown in Fig. 6(a). Overall, it was observed that the schedule of dimensions predicted the digital model closely matching with the RDSO drawings. It was observed that the change in overall length from the digital data was found to be 2 mm, whereas the same was found to be 10 mm measured manually at the site. In case of distance between the centre of bearings, the difference between RDSO and measured and digitally recorded data was found to be 5 and 9 mm, respectively. In case of clear span, the manually measured data is not available, however, the digital data was recorded and shown in Table 3. The maximum difference between the RDSO and digital data was found to be 18 mm for the exterior span L0-L1 (Tto End). However, the difference between RDSO and digital data was found to be very small in the case of interior span. The schedule of dimensions at the cross-sectional view as per RDSO and predicted data from the digital model are shown in Table 4.

The schedule of the dimension diagram of cross-sectional view is shown in Fig. 6(b). The manual measurement on the cross-section views is always very difficult, therefore the cross-section views were not recorded manually. It was observed that the

digitally predicted track gauge spacing and distance between centres of the main girders was found to be the same as that of RDSO measurement. However, the difference between RDSO and digitally measured centre to centre distance between intersections and inner width was found to be 78 and -70 mm which is important to check these components and strengthen it accordingly. Further, it is to note that the small components such as sleeper height, contact wire height and Distance between knee bracings at contact wire height were not able to record digitally and the reason may be due to the lack of plan and missions involved in the PoC.

Table 3 - Schedule of dimensions at elevation side.

Description	As per RDSO drawing (mm)	Manual data (mm)	Digital data (mm)	Difference b/w RDSO and Manual (mm)	Difference b/w RDSO and Digital (mm)
Overall length	47850	47840	47848	10	2
Centre to centre of bearings	47240	47235	47231	5	9
Clear span	45700	45660	45676	40	24
L0-L1 (Tto End)	5905	-	5887	-	18
L1-L2	5905	-	5902	-	3
L2-L3	5905	-	5907	-	-2
L3-L4	5905	-	5907	-	-2
L4-L5	5905	-	5907	-	-2
L5-L6	5905	-	5905	-	0
L6-L7	5905	-	5906	-	-1
L7-L8 (BEAS End)	5905	-	5906	-	-1



(a)



(b)

Fig. 6 - Typical bridge (a) elevation and (b) cross sectional view with related dimensions.

Table 4 - Schedule of dimensions at cross-sectional side.

Description	As per RDSO drawing (mm)	Digital data(mm)	% Error b/w digital and RDSO
Track Gauge	1676.0	1674.0	2
Centres of Intersections	7315.0	7237.5	78
Inner width	4725.0	4795.0	-70
Centres of main girders	5180.0	5177.0	3
Sleeper height	950.0	950.0	NA
Contact wire height	Varies	5340 (5675 at catenary)	NA
Distance between knee bracings at contact wire height	N/A	3459.6	NA

3.2 Camber

Successive loss of camber over several observations is a cause of worry. This may be on account of (1) Heavy overstressing of girder members, (2) Overstressing of joint rivets at a splice in a plate girder or at the gusset in case of open web girder, (3) Play between rivet holes and rivet shanks. As per Bridge Manual, Part-E (2020) [33], steel triangulated (OWG) girders are provided with camber to compensate for deflection under load. The camber should be retained during the service life of the girder to avoid distressing steel girders. Camber was measured by two methods i.e., differential of top of cross girders levels and offset from chord joining the centre of cross-sections of the bottom chord.

3.2.1 Differential of top of cross girders levels

The differential of top of cross girders levels is a convention way of measuring camber on the field. The same technique was used for manual measurement. The measurements on both left side and right-side camber recorded in the year 2011, 2016 and 2011, were used for the comparison with the manual measurement and digital measurement, see Tables 5 and 6. It was observed that the camber is reduced with increase the time from 2011 to 2021. However, the digital measurement recorded in the year 2021 found in good agreement with the manual measurement.

Table 5 - Left side camber comparison with manual and digital measurement.

Joint No	2011	2016	May 2021	Aug 2021	Manual (reverified) data, Aug 2021 (mm)	Digital Data Aug 2021 (mm)
L0	0	0	0	0	0	0
L1	10	10	9	10	10	12
L2	23	20	20	23	21	20
L3	38	32	30	33	29	30
L4	35	35	35	36	35	29
L5	35	30	28	27	25	24
L6	30	20	20	23	22	21
L7	20	10	10	11	12	14
L8	0	0	0	0	0	0

Table 6 - Right side camber comparison with manual and digital measurement.

Joint No	2011	2016	May 2021	Aug 2021	Manual (reverified) Data, Aug 2021 (mm)	Digital data Aug 2021 (mm)
R0	0	0	0	0	0	0
R1	10	10	10	8	8	8
R2	20	20	18	19	20	19
R3	38	35	36	33	33	28
R4	35	38	36	34	35	30
R5	38	35	34	31	28	33
R6	35	20	22	21	20	21
R7	20	10	10	8	8	7
R8	0	0	0	0	0	0

3.2.2 Alignment of center of cross section of bottom chord

This method has been developed to better align with the engineering concept of camber. This is a method that cannot be undertaken in the field and cannot be compared with the indirect method that is given in Section 3.2.1. It is envisaged that as more data builds up with successive digital inspections of a bridge, a better clarity on camber will emerge. As sample results, only the camber at L4 of the left bottom girder was measured. It was observed that the differential of top of cross girders levels which is a conventional method, measured digitally the camber as 29 mm, Table 5, whereas the same was found to be 28 mm by using this method. It was concluded that the dimensional measurements through automate technology that are comparable with the previous inspection reports within a range of ± 5 mm, indicating photogrammetry along with LiDAR is a dependable alternative technology for bridge inspection.

3.3 Distortion

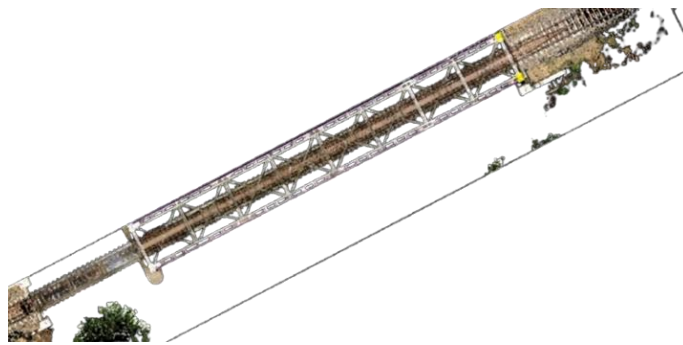
There are two different distortions such as lateral distortions and torsional distortions taken into consideration. In the field, distortion is essentially lateral distortion, either just checked visually or measured as the offset of the centre of a member from a chord connecting the end points of the same member. In the present study, the same methodology has been used to measure lateral distortion using the digital model, see Fig. 7. In addition to the above, utilizing the flexibility provided by a digital model, torsional distortion was measured. Torsional distortion is a more severe case led to ascertaining the condition of a bridge. In open web girders, top chord members carrying compressive stress if not sufficiently restrained, led to distortion. Diagonal web members particularly if they are made up of flats and most likely at mid span due to stress reversal and vibration during passage of train, lead to distortion. Bottom chord members which carry tension and longitudinal forces if not properly braced, lead to distortion. The most likely location is near the bearings in case of frozen bearings, leading to distortion. Top lateral and portal bracings are likely to distort due to excessive lateral forces. Distortion is also possible if longitudinal movement of girders due to temperature variation is arrested on account of frozen bearings. Sometimes web members, i.e. diagonal, vertical and end rakers through girder bridges, are hit by moving loads due to shifting of load in wagons, particularly over dimensioned consignment (ODC).

3.3.1 Lateral distortion

Lateral distortion measured on right and left bottom girder was found to be in range of 10 mm, see Table 7. It was observed that the distortion of this girder comes out to be within permissible limits of 0.001 L (i.e. 0.001 of 45.7 m) as per Appendix II of IRS steel bridge code.

Table 7 - Lateral distortion of left and right bottom girder.

Span	Distortion (mm)	Span	Distortion (mm)
L0 Tto end	0	R0 Tto end	0
L1	4	R1	-15
L2	5	R2	-8
L3	9	R3	-6
L4	8	R4	-2
L5	8	R5	0
L6	3	R6	4
L7	5	R7	6
L8 Beas end	0	R8 Beas end	0

**Fig. 7 - Distortion by offset from chord.**

3.3.2 Torsional distortion

Torsional distortion was measured using the length of diagonals at different cross- sections of the left bottom girder and typical torsional distortion measurement is shown in Fig. 8. Based on the digital measurement, the torsional distortion is recorded as diagonal d1 and d2 at different sections, see Table 8. Any significant difference in the length of diagonals (d1, d2) reveals a suspected case of torsional distortion that may be further investigated using bridge instrumentation. It was observed that the selected sections show no evidence of torsional distortion and the difference in the d1 and d2 was found to be insignificant.

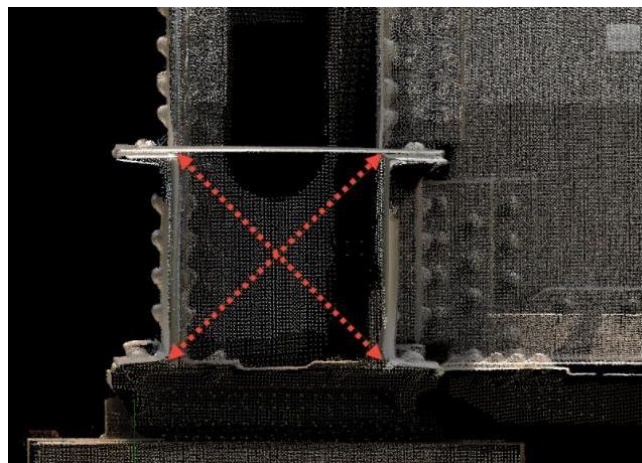
**Fig. 8 - Distortion of bottom girder**

Table 8 - Distortion of bottom girder.

Section No.	d1 (mm)	d2 (mm)
1 st x-section	569.320	569.320
2 nd x-section	572.349	568.153
3 rd x-section	565.000	565.000
4 th x-section	564.875	564.210

3.4 Rail Levels

The vertical distance between the rail level and the bed block was measured, as shown in Table 9. The results indicated that the overall level difference is negligible, with no significant variation observed in the levels of the rails, track, or guard rails. This suggests a high degree of accuracy in the measurements. It can be concluded that the integration of LiDAR and UAV-assisted photogrammetry technologies effectively combines the strengths of both methods, resulting in a comprehensive and reliable assessment. Notably, the maximum level deviation recorded was only 5 mm.

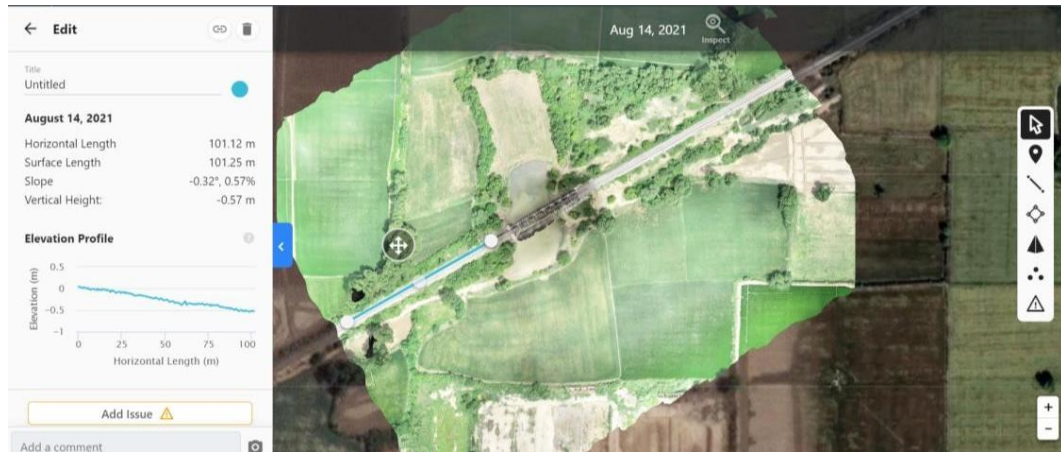
Table 9 - Rail levels.

Dimension	Manual data (mm)	Digital data (mm)
Track to guard rail	NA	319.219 - 315.531
Span 1		
Beas End	1750	1755
TTO End	1762	1763
Span 2		
Beas End	1765	1763
TTO End	1765	1761

Further, the rail levels along the longitudinal section of 100m track on from Tto end to Beas end, were measured, see Fig. 9. The measured location is marked in a blue colour for both tto and beas end. Also, the rail levels are measured at every 5th sleeper and recorded digitally as shown in Table 10. It was observed that the sleeper levels at left and right-side rails were found to be almost the same and maximum deviation was found to be 6 mm, i.e., 300 mm and 306 mm at left and right side, respectively near tto end. However, the difference between the left and right-side rail was found to be almost negligible.

Table 10 - Rail level at every 5th sleeper.

LL0 Beas End (mm)	RL0 Beas End (mm)
315	315
320	319
321	319
323	322
327	325
328	328
331	329
333	333
329	331
327	327
322	323
319	321
317	320
308	313
300	306
291	295
283	286
287	285
LL8 Tto End	LL8 Tto End



(a)



(b)

Fig. 9 - Longitudinal section of 100m track on (a) tto end and (b) beas end.

3.5 Creep measurement

The creep is calculated through the measurement of distance between adjacent span or distance between end span and abutment. The creep measurement through the manual data and digital data are compared, see Table 11. The typical creep at the bracket and beas end is shown in Fig. 10. It was observed that the manually measured creep distance at the bracket found to be 35-42 mm whereas the same digitally measured data found to be 77-85 mm. The difference between the manually measured data and digitally measured data is almost 100% and the regular inspection may be required at such a location and to be retrofitted or strengthened with suitable techniques.

Table 11 - Creep measurements.

Description	Manual data (mm)	Digital data (mm)
Beas end (left)	105	108.0
Beas end (right)	102	115.0
Bracket – Beas	42	77.3
Bracket – Beas	35	85.0
TTO end (left)	170	187.0
TTO end (right)	170	185.0

Table 12 - Girder twist.

Span	D1 (mm)	D2 (mm)	Difference
L7-R7	7763	7770	-7
L6-R6	7902	7905	-3
L5-R5	7895	7895	0
L4-R4	7915	7912	3
L3-R3	7895	7895	0
L2-R2	7920	7902	18
L1-R1	7778	7775	3

**Fig. 10 - Typical creep at the end of bridge.**

3.6 Eccentricity

Open web girder bridge assembly twist is called eccentricity which is determined by measuring the diagonals at all 7 cross girder locations in bridge cross-section, see Fig. 11. The eccentricity on open web girder bridge assembly twist was measured as shown in Table 12. It was observed that the difference is negligible for the overall lengths of the diagonals and there is no evidence of eccentricity of the bridge assembly in the vertical plane. However, the maximum deviation of 18 mm eccentricity was observed for the span L2-R2 and it is concluded that the inspection indicating photogrammetry along with LiDAR is a dependable alternative technology for bridge inspection with high accuracy.

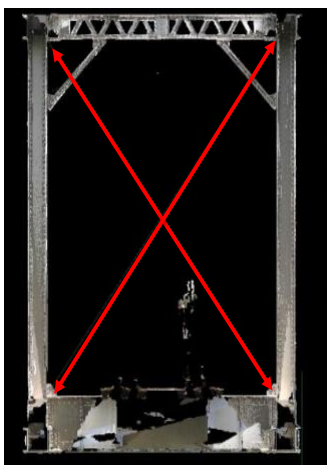
**Fig. 11 - Typical eccentricity measurement.****(a)****(b)****Fig. 12 - (a) Missing rivet on diagonal member and (b) rusting on sway bracing.**

Table 13 - Visual inspections through the high-resolution photographs.

S. No.	Area/Location	Remarks
1	Protection Works	Visual examination of hi-resolution photographs with an option of machine learning in future developments. Machine examination by comparison to drawings and earlier pictures to be examined.
2	Abutments	
3	Piers	
4	Bed Blocks	
5	Bearings and vicinity	
6	Lateral Bracing	
7	Sleeper Seats	
8	Flooring arrangement and connections with bottom chords, cross girders	
9	Gusset connection of top lateral bracing to top boom.	
10	Bridge Deck	

3.7 Visual inspections through the high-resolution photographs

An important aspect of the methodology defining Critical Areas of Particular Interest (CAPI) for which high resolution photographs were to be taken, see Figs. 12(a-b). With the digital model, high resolution photos of any area can be viewed from multiple angles and analyzed for any deficiency or failure. These deficiencies such as rusting, missing or loose rivets (taking cue from rusting around them), hits marks, failure of masonry structures, flash marks from OHE, bearing abnormalities that can be possibly noticed. Accordingly, 2200 pictures were taken and are being sorted and analyzed. Visual inspections were performed through sample checks on different areas and locations of the bridges, see Table 13. It is concluded that the hi-resolution photographs with an option of machine learning in future developments and the machine examination may be compared with the drawings and previous inspection/pictures to be examined.

4 Conclusions

The present study focused on a methodology to automate technical inspections of a single span steel girder bridge of 45.7 m through the mixed approach by photography along with LiDAR scan. The Proof-of-Concept (PoC) was developed as high-fidelity digital models to accomplish the 16 missions. The high-fidelity digital models of bridge lead to flexibility in viewing, analyzing and measuring different parameters such as schedule of dimensions diagram, camber measurements, distortions, rail levels, creep measurement and eccentricity. Further, the parameters measured from the digital model were compared with the limiting values as per RDSO, manually measured data available in the previous inspection report. Based on the comprehensive structural health monitoring of bridges, following conclusions were drawn.

- It was observed that the dimensional measurements obtained through automated technology were comparable with the drawings and previous inspection reports, within a range of ± 5 mm, indicating that photogrammetry combined with LiDAR is a dependable alternative technology for bridge inspection.
- Furthermore, cross-sectional views of the bridge could be extracted at any desired longitudinal or lateral plane, and critical dimensions including camber and distortion could be measured with ease using methodologies that are not feasible through manual field measurements
- It was concluded that the distinct, yet complementary advantages of LiDAR and UAV-assisted photogrammetry technologies brought the best of both worlds. The digital reality model, with underlying high-resolution imagery, enabled visual inspection of the bridge in far greater detail than is humanly possible during on-site inspections, with the added advantage of long-term digital record keeping.

- It was also concluded that the point cloud data captured by LiDAR provides precise measurements of all dimensions, including those that are not possible to obtain during manual inspection.

5 Future Development

As future development, some of the areas that may be tagged in light of structural health monitoring are as follows.

- Measurements can be automated using feature recognition tools.
- Failure detection can be automated using various image processing techniques and machine learning.
- Image processing, pattern recognition techniques, and other types of sensors such as infrared can be explored for detecting typical failures like loose bolts and rivets.

Robotic Process Automation (RPA) platforms are being developed and are expected to enter the market soon; these platforms integrate both RGB and LiDAR cameras, which are likely to significantly enhance measurement accuracy.

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