TECHNICAL PAPER

JOURNAL OF THE SOUTH AFRICAN INSTITUTION OF CIVIL ENGINEERING
ISSN 1021-2019 (print) | ISSN 2309-8775 (online)
Vol 64 No 3, September 2022, Pages 50–57, Paper 1439

Enhanced methodology for visual bridge inspections in South Africa

L Kemp, W J vd M Steyn, M P Roux

This paper introduces the application of technology solutions into the realm of bridge inspection methodologies in South Africa, aiming to enhance the current visual bridge inspection methodology. Unmanned Aerial Vehicles (UAVs) can be used as an alternative to collect bridge image data, and point cloud models can be created from captured images by using photogrammetry software. For this study, accredited bridge inspectors were approached to complete TMH 19 inspection sheets of bridge structures using only the point cloud models and captured images, as a proposed new inspection methodology. This paper compares historic inspection ratings and the point cloud inspection ratings to investigate the effectiveness and practicality of the new proposed inspection methodology. The study concluded that bridge inspectors could identify and rate critical defects of bridge structures using the new inspection methodology, but there are limitations and specific use cases that need to be identified.

BACKGROUND

Bridge structures are key components to the success of a country's transportation system. South Africa has thousands of bridge structures forming part of its road network. These structures are owned by national authorities, provincial authorities and municipal authorities responsible for the maintenance and safety of these structures. Routine inspections and maintenance are important to preserve the structural integrity of bridge structures for a maximum design life.

The Council for Scientific and Industrial Research (CSIR) has been involved in the development of various road-related management systems. One of these management systems is STRUMAN, which started as a Bridge Management System (BMS) but has since evolved into a structure management system for road-related structures (Nordengen & Nell 2005).

The ability to collect, store and utilise large datasets is transforming the world. Technology is rapidly evolving and should be utilised to collect valuable data. Improving the reliability of information and the constancy of data collection methods for bridge management systems could assist with decision-making and assigning appropriate maintenance budgets. International studies have shown success in utilising technology for visual bridge inspections, and the need to adopt these methods in a South African context has been identified (Wells & Lovelace 2018; Ciampa *et al* 2019; Jahanshahi *et al* 2009; Perry *et al* 2020; PIARC 2018; Hallermann *et al* 2018).

The practical use of technologies such as Unmanned Aerial Vehicles (UAVs) and photogrammetry to enhance bridge inspections is currently being investigated by the CSIR. This ongoing project conducted a proof-of-concept study which delivered the potential to enhance the visual bridge inspection methodology in South Africa (Kemp *et al* 2021).

The South African National Roads Agency Limited (SANRAL) indicated that, as part of their bridge management, the use of UAVs has been investigated. Videos were captured of bridge bearings and then viewed by qualified inspectors. This method proved to be time-consuming, and had limitations. The UAVs had to be licenced with the Civil Aviation Authority and the regulations did not permit UAVs to be operated over roads. Inspectors were also unable to inspect confined spaces. Although SANRAL does not make use of UAVs for bridge inspections, the organisation acknowledged the advantages of using UAVs for specific applications (Kruger & Nyokana 2018).

LANA KEMP is a Senior Civil Engineer and Researcher at the Council for Scientific and Industrial Research (CSIR) in the Smart Mobility Cluster. Her research focus includes asset management projects, technology applications for bridge inspections and heavy-vehicle infrastructure impact assessments. She obtained BEng Civil Engineering, BEng Hons Transportation Engineering and MEng Transportation Engineering degrees from the University of Pretoria. She has authored and co-authored 11 conference papers. Currently she is registered as a Candidate Engineer with the Engineering Council of South Africa.

Contact details:
Department of Civil Engineering
University of Pretoria
Private Bag X20
Hatfield 0028
South Africa

CSIR Smart Mobility
Meiring Naudé Road
Pretoria 0081
South Africa
T: +27 12 841 3964
E: lkemp@csir.co.za

PROF WYNAND STEYN (Pr Eng, FSAICE, FSAAE) is Head of Department and Professor of Civil Engineering, and Chair of the School of Engineering at the University of Pretoria. He is a pavement engineer with research interests in vehicle-pavement interaction, accelerated pavement testing, engineering materials, and civiltronics. He has authored and co-authored 55 journal papers and 111 conference papers. He is Associate Editor of the *International Journal for Pavement Engineering* and the *International Journal of Pavement Research and Technology*, and has a B3 National Research Foundation (NRF) rating.

Contact details:
Department of Civil Engineering
University of Pretoria
Private Bag X20, Hatfield 0028, South Africa
T: +27 12 420 2171
E: Wynand.steyn@up.ac.za

MICHAEL ROUX (Pr Eng) is a Principal Civil Engineer at the Council for Scientific and Industrial Research (CSIR) in South Africa. He obtained a BEng in Civil Engineering (1982) and an M Eng in Structural Engineering (1984) from the University of Stellenbosch and a Master's in Business Leadership (MBL) from the University of South Africa (1996). He worked in the municipal roads environment for 15 years and during this time he was involved in roads and stormwater construction and maintenance projects and asset management of road-related infrastructure. He has been with the CSIR since 2002 where he is mainly involved in road asset management, bridge management systems, and the development and implementation of overload control strategies for road authorities. His areas of interest also include the analysis of road wear caused by heavy vehicles. He has author and co-authored 12 papers and more than 50 research reports.

Contact details:
CSIR Smart Mobility
Meiring Naudé Road, Pretoria 0081, South Africa
T: +27 12 841 2666
E: mproux@csir.co.za

Keywords: visual bridge inspections, 4IR technology, unmanned aerial vehicles (UAVs), point cloud models

Kemp L, Steyn WJvdM, Roux MP. Enhanced methodology for visual bridge inspections in South Africa.
J. S. Afr. Inst. Civ. Eng. 2022:64(3), Art. #1439, 8 pages. http://dx.doi.org/10.17159/2309-8775/2022/v64n3a6

A three-phased study conducted by the Minnesota Department of Transport together with industry stakeholders investigated the use of UAVs for bridge inspections. The study focused on rules and regulations, UAV hardware and the ability of UAVs to collect quality inspection data. The ability of UAV technology to conduct bridge inspections was confirmed by the Minnesota study, but the practicality to conduct network inspections of thousands of structures is yet to be determined (Wells & Lovelace 2018).

PROBLEM STATEMENT

In South Africa, principal visual inspections for all bridge structures are required every five years (COTO 2020a; COTO 2020b). Bridge inspectors and senior bridge inspectors are highly qualified and experienced persons. For such individuals to inspect all bridges and major culverts in a defined region is a time-consuming and costly exercise. Smaller authorities and metros do not always have the necessary funds available to perform principal bridge inspections, as required. Budget and capacity constraints often lead to inspections not being executed or the use of unqualified inspectors, which results in poor quality inspection data. High-quality inspection data as input to a BMS is essential to determine the current conditions of structures. Accurate maintenance budgets and schedules are necessary to protect the structural life and integrity of bridge structures and to ensure the safety of all users.

Enhancing the inspection methodology to capture image data and to perform visual bridge inspections, utilising new technologies such as UAVs and point cloud models, has the potential to improve the quality and consistency of inspections.

OBJECTIVES

The objectives of this paper are to:

- determine whether visual bridge inspections can be performed using point cloud models and images only, and
- determine if accredited bridge inspectors can identify and rate critical defects using only point cloud models and captured images.

SCOPE

The original study consisted of the following components and activities:

1. Capture image data for four bridge structures using UAVs.
2. Process captured images to create point cloud models using photogrammetry software.
3. Approach accredited bridge inspectors to identify defects, rate defects and complete TMH 19 inspection sheets, using only point cloud models and captured images of the bridge structures.
4. Compare the point cloud inspection sheets and ratings captured using the new inspection methodology and historic inspection sheets from traditional TMH 19 inspections.

The scope of the paper includes the capturing of image data of four bridge structures, and the visual inspection of a large and medium-sized bridge using the new proposed inspection methodology. This paper focuses on the practicality and effectiveness of the new inspection methodology and relies on historic inspection data. The results of the inspections were subjective to the bridge inspectors' expertise and experience.

METHODOLOGY

Image data of four bridge structures was captured from two different sites in 2020, using a UAV with a mounted camera. These structures form part of the Gauteng provincial road network.

The captured image data was processed using photogrammetry software to create point cloud models. Two independent COTO-accredited senior bridge inspectors were approached to conduct visual inspections and complete inspection sheets using only the point cloud models and captured images of two bridge structures.

The inspectors attempted to identify and rate defects following the TMH 19 Degree, Extent and Relevancy (DER) rating method (COTO 2020b). The ratings of the identified defects were compared to the historic inspection sheets of the structures, as captured in the CSIR STRUMAN BMS system. It was assumed that no maintenance or rehabilitation had been done to the structures since the previous principal bridge inspections in 2016, as the same defects were identified during the point cloud inspections. The structure defect ratings were evaluated individually and where differences were noted in the new DER defect ratings, further investigations were conducted.

Capturing image data

Premier Mapping Africa was appointed by the CSIR to capture the image data for the identified structures using a UAV. Premier Mapping Africa manage aerial survey projects and is licenced to offer aerial survey services using full-sized aircraft as well as remotely piloted aerial vehicles as per South African regulations (SACAA 2017). Premier Mapping Africa holds an Air Operator Certificate (AOC) for manned aerial surveys and a Remotely Piloted Aircraft Systems (RPAS) Operators Certificate for RPAS aerial photography. Premier Mapping Africa obtained permission for the flight missions from the South African Civil Aviation Authority (SACAA). The CSIR requested permission from the landowner (the Gauteng Department of Roads and Transport (GDRT)) to capture images of the structures using a UAV.

Historic inspection data for the four structures, including all the identified defects, the assigned DER ratings of defects, the condition indices (Priority Condition Index (PCI)), inspection and inventory photos and key dimensions, were available in the CSIR STRUMAN BMS database. Details on these structures are presented in Table 1 and Figure 1. The diagrams with key dimensions are not drawn to scale and are only for conceptual purposes.

Image data of the four structures using a UAV was captured on 17 February 2020

Table 1 Details of the inspected structures

Bridge	Class	Structure number	PCI	Condition category
SITE 1				
Bridge 1	Large bridge	D631_01N_B4435	64.30	Fair
Bridge 2	Medium bridge	D631_01N_B4095	93.80	Very good
SITE 2				
Bridge 3	Medium bridge	D2377_01N_B1106	95.25	Very good
Bridge 4	Medium bridge	K175_01N_B5102A	74.44	Good

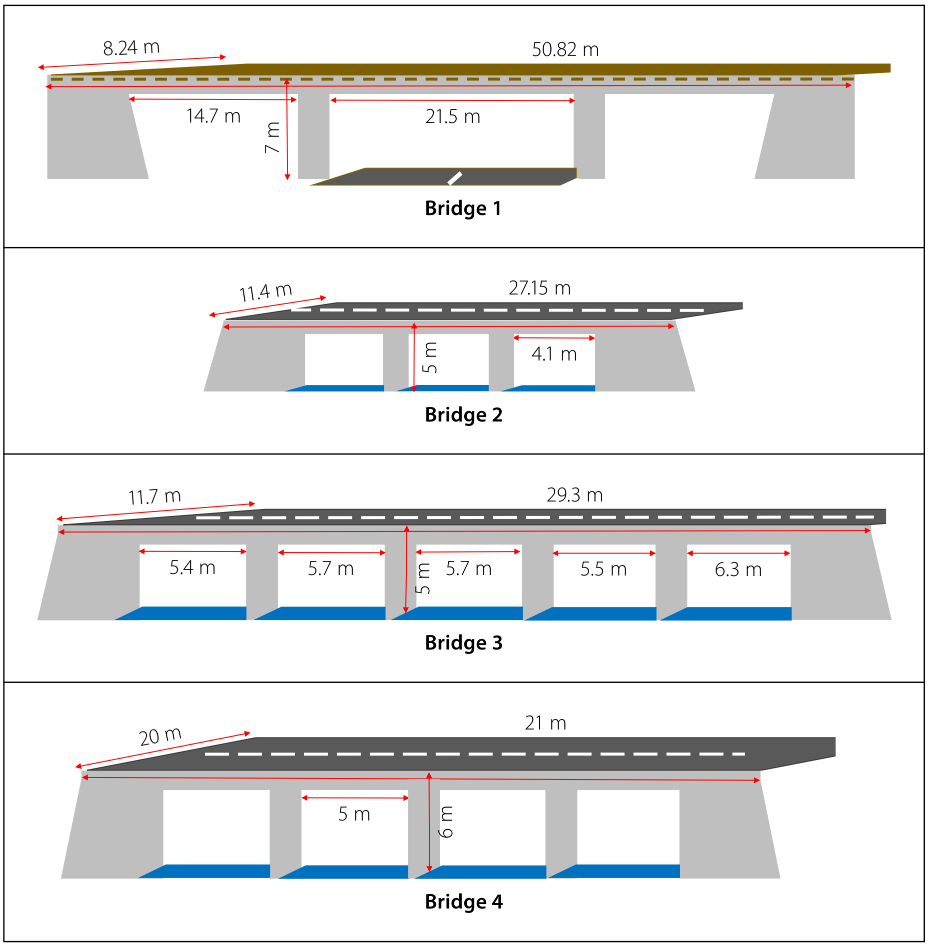

Figure 1 Diagrams of key dimensions of bridges

and 19 November 2020 from two different sites. The structure locations are shown in Figure 2. The data recorded during the image capturing of structures from Site 1 and Site 2, and the equipment used to capture the images, are summarised in Table 2.

Point cloud models

The images captured during the inspections were processed using Pix4D photogrammetry software to create point cloud models. A desktop core i7 with a 64 GB SSD and 128 GB RAM computer was used to process the images. The total processing time to create a point cloud model from the captured images was approximately five to six hours per structure. An accuracy of 20 mm to 40 mm was attained in generating the point cloud models, with an average georeferencing GPS error of 1 m. After the images had been processed, Pix4D Mapper was used to view the point cloud models. The point cloud models created from the captured structure images are shown in Figure 3.

Point cloud inspection ratings

Two COTO accredited senior bridge inspectors each inspected two bridge structures, using only the point cloud models and captured images. The inspectors participating in this study are active, accredited bridge inspectors with a minimum of 15 years bridge design experience. They had not inspected the structures previously and thus had no prior knowledge of the defects. Comments on the practicality and limitations of the new inspection methodology were noted.

The structures selected for inspection were different in class and size and had defects recorded on historic inspection sheets. The following two structures were selected for inspection:

- Bridge 1, a large bridge
- Bridge 2, a medium bridge.

Only two structures, that are different in size and class, were selected for inspection as a sample. Bridges 3 and 4 had usable data and models, but they were also medium-sized bridges (similar to Bridge 2). External professional bridge inspectors were used,

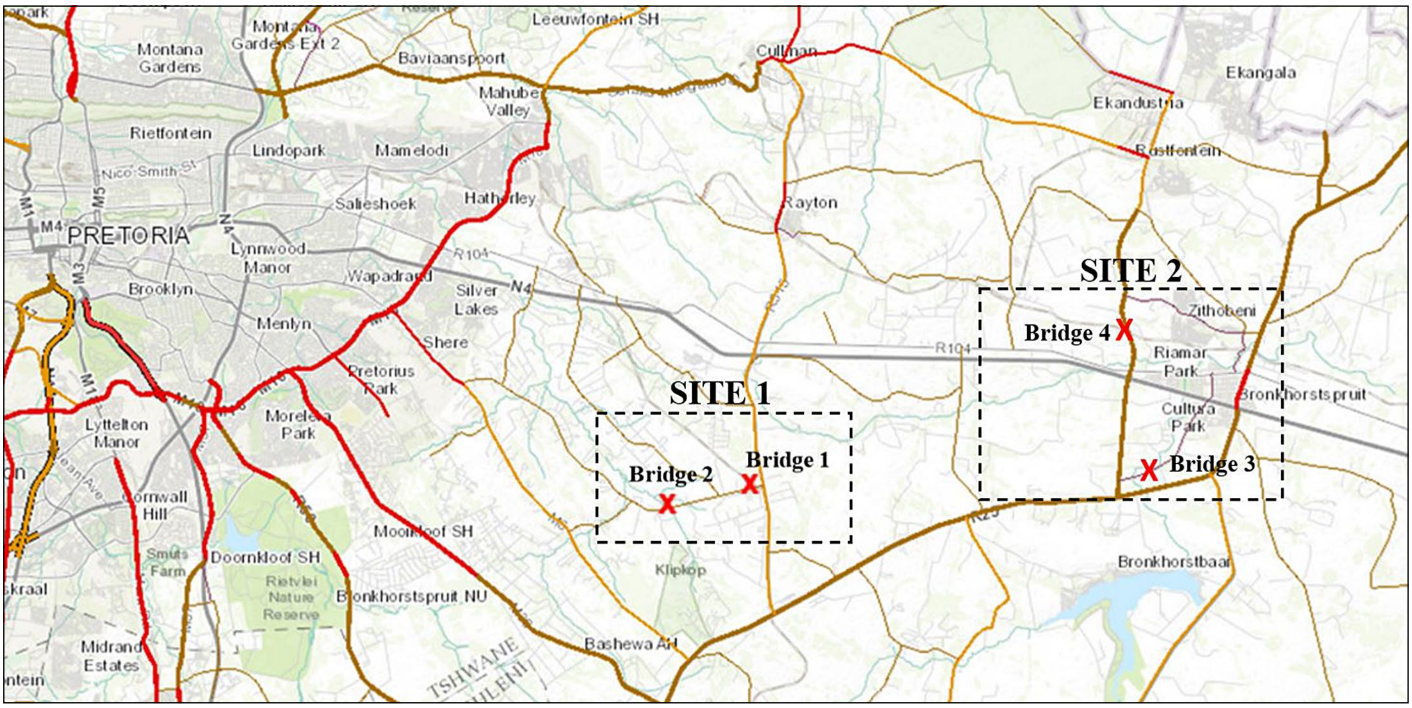

Figure 2 Location of the inspected structures (Gauteng RAMS Geospatial Decision Support System)

Table 2 Summary data of the captured structures

Bridge	Duration [min]	Technical equipment used	Battery change	Total images captured	Size of the image file [GB]	Size of point cloud model [KB]
SITE 1						
Bridge 1	45	**UAV:** DJI Inspire 2 **Camera:** Zenmuse x4S (20 MP)	Yes	462	3.75	318
Bridge 2	30	**UAV:** DJI Inspire 2 **Camera:** Zenmuse x4S (20 MP)	No	359	2.88	250
SITE 2						
Bridge 3	35	**UAV:** DJI Inspire 2 **Camera:** Zenmuse x4S (20 MP)	Yes	429	3.49	331
Bridge 4	40	**UAV:** DJI Inspire 2 **Camera:** Zenmuse x4S (20 MP)	Yes	340	2.72	241

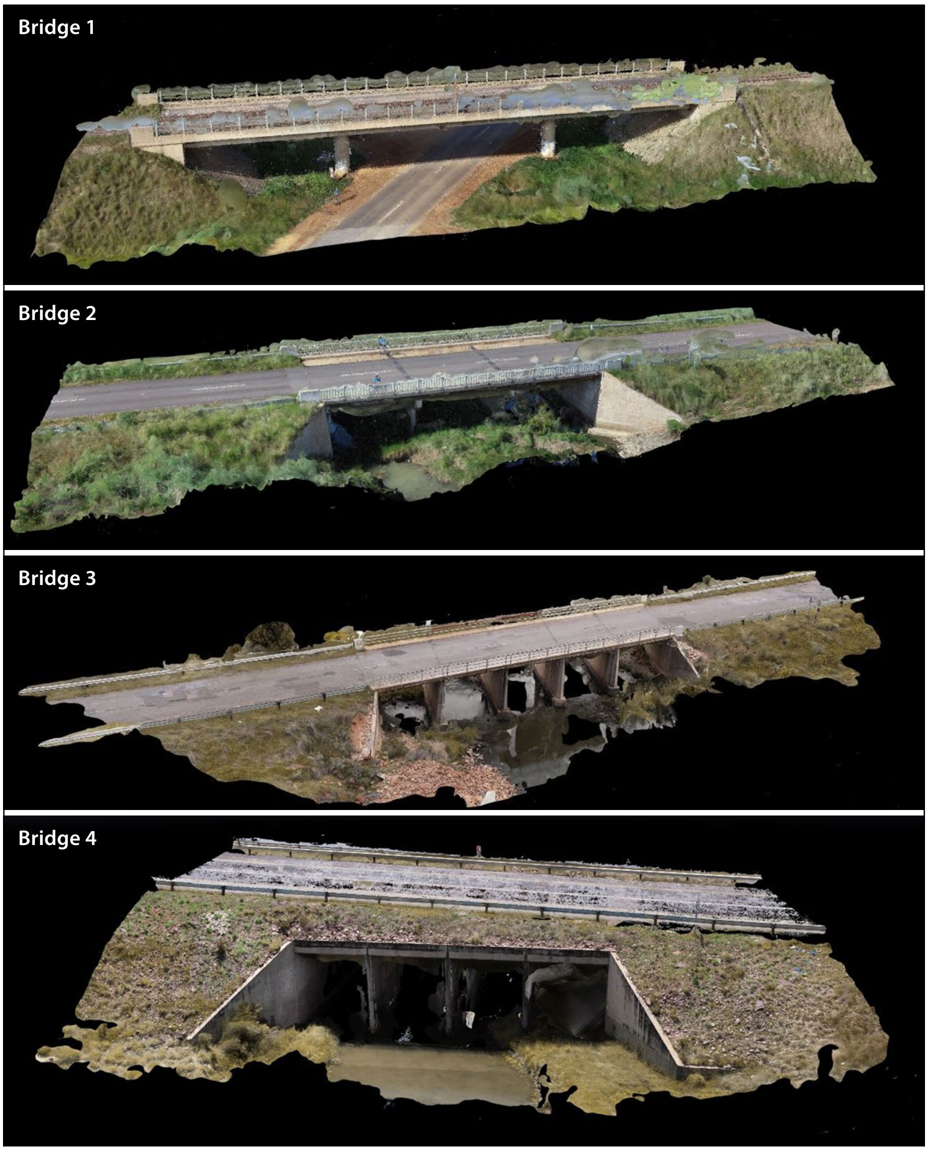

Figure 3 Generated point cloud models from captured images

and they were only able to inspect two structures in the available time.

The following methodology, using Pix4D Mapper, was proposed to identify defects, rate the defects, and complete an inspection sheet for each structure:

1. Open Pix4D Mapper on the additional computer monitor, select the structure for inspection and use the "Map View" in Pix4D Mapper to comprehend the spatial orientation of the structure, and number the structure elements according to convention.
2. Use the point cloud model as a spatial referencing tool. Start inspecting the structure systematically. Inspect each structure element by selecting a point of interest on the point cloud model, view the list of generated images and select the image with the preferred detail, lighting, and angle.
3. Rate defects identified on the element, using the DER rating system as prescribed in the TMH 19 manual, and capture the ratings and corresponding remedial activities on the inspection sheet.
4. Repeat steps 2 and 3 for all structure elements.

Historic inspection data

To determine the effectiveness of the new inspection methodology and whether the same defects could be identified and rated using only point cloud models and captured images, the inspection ratings of the point cloud inspections were compared to historic TMH 19 visual inspection data.

The structures selected for this study were previously inspected in 2016 as part of the Gauteng provincial road network principal visual bridge inspections. Although 2016 inspection data was used for comparison, it can be assumed that no maintenance or rehabilitation has been done to the structures since then, as the same defects were identified during the point cloud inspections. The structure defect ratings were evaluated individually, and where differences were noted in the new DER ratings, further investigations were conducted.

RESULTS

The bridge inspectors each completed inspection sheets using the new proposed inspection methodology. They identified defects and assigned DER ratings to the defects. A summary of the identified defect types and corresponding DER ratings for

Table 3 Identified defects and DER ratings

Legend	Difference in DER ratings	0	1	2	3	4

Defect	Element and DER rating											
	Historic Inspection				Inspector 1				Inspector 2			
		D	E	R		D	E	R		D	E	R
Bridge 1												
1. Interlocking blocks missing	04. Approach embankment protection works				04. Approach embankment protection works				01. Approach embankment			
	A2	1	1	1	A2	1	2	1	A2	1	2	1
2. Vegetation growing through interlocking paving on abutment	04. Approach embankment protection works				04. Approach embankment protection works				04. Approach embankment			
	A2	1	1	1	A1	2	2	2	A1	2	1	1
3. Abutment seating cracks	06. Abutments				06. Abutments				06. Abutments			
	A1	3	1	3	A1	1	2	1	A1	1	1	1
	A2	3	1	3	A2	1	2	1	A2	1	1	1
4. Spall on wing wall	07. Wingwall/Retaining walls				07. Wingwall/Retaining walls				07. Wingwall/Retaining walls			
	A2	0	–	–	A2	1	1	1	A2	1	1	1
5. Debris on deck surface	10. Kerbs/Sidewalk				10. Kerbs/Sidewalk				10. Kerbs/Sidewalk			
	AS	0	–	–	AS	1	2	1	A1	1	1	1
6. Guardrails missing	12. Pier protection works				12. Pier protection works				12. Pier protection works			
	P1	0	–	–	P1	3	4	3	P1	2	4	3
	P2	0	–	–	P2	3	4	3	P2	2	4	3
7. Missing abutment drainage/ blocked drainage	16. Support drainage				16. Support drainage				16. Support drainage			
	A1	0	–	–	A1	2	3	2	A1	3	4	2
	A2	0	–	–	A2	2	3	2	A2	3	4	2
8. Blocked joint/damaged gland of claw joint	17. Expansion joints				17. Expansion joints				17. Expansion joints			
	A1	0	–	–	A1	3	3	2	A1	3	4	2
	A2	0	–	–	A2	3	3	2	A2	3	4	2
9. Impact damage	20. Deck slab				20. Deck slab				20. Deck slab			
	S2	0	–	–	S2	2	1	1	S2	1	1	1
Bridge 2												
1. Settlement of approach embankments	01. Approach embankment				01. Approach embankment				01. Approach embankment			
	A1	0	–	–	A1	2	3	2	A1	1	1	1
	A2	0	–	–	A2	2	3	2	A2	1	1	1
2. Guardrails not attached to end blocks	02. Guardrails				02. Guardrails				02. Guardrails			
		0	–	–		3	4	3		3	4	3
3. Waterway debris and vegetation	03. Waterway				03. Waterway				03. Waterway			
		2	2	2		0	–	–		0	–	–
4. Abutment crack	06. Abutments				06. Abutments				06. Abutments			
	A1	1	1	1	A1	0	–	–	A1	0	–	–
5. Vegetation on road surface/ hidden guardrail	08. Surfacing				08. Surfacing				10. Kerbs/Sidewalk			
		3	3	2		1	2	1		1	1	1
6. Scuppers too short and blocked	09. Superstructure drainage				09. Superstructure drainage				09. Superstructure drainage			
		2	4	1		2	4	2		1	4	1
7. Corroded handrails	12. Parapet				12. Parapet				12. Parapet			
		2	4	1		0	–	–		0	–	–
8. Spall on pier	14. Piers and columns				14. Piers and columns				14. Piers and columns			
	P1	1	2	1	P1	0	–	–	P1	0	–	–
	P2	1	2	1	P2	0	–	–	P2	0	–	–
9. Joint needs new asphalt plug	17. Expansion joints				17. Expansion joints				17. Expansion joints			
	A1	0	–	–	A1	2	4	1	A1	2	4	2
	A2	0	–	–	A2	2	4	1	A2	2	4	2
10. Faded clearance signs and missing structure number	21. Miscellaneous				21. Miscellaneous				21. Miscellaneous			
		0	–	–		0	–	–		1	1	1

Table 4 PCI and condition category of point cloud inspections

Class	Structure number	Inspections	PCI	Condition category
Bridge 1				
Large bridge	D631_01N_B4435	Historic	64.30	Fair
		Inspector 1	82.99	Good
		Inspector 2	82.97	Good
Bridge 2				
Medium bridge	D631_01N_B4095	Historic	93.80	Very good
		Inspector 1	90.99	Very good
		Inspector 2	90.96	Very good

Bridge 1 and Bridge 2, captured during the inspections, are shown in Table 3.

The bridge inspectors were unable to inspect all the bridge elements using the new inspection methodology. The elements captured as "unable to inspect" on the inspection sheets for Bridge 1 included abutment foundation, pier foundations and bearings. The inspectors were able to inspect all the Bridge 2 elements. Different colours were used to illustrate the variance in the point cloud inspection ratings compared to the historic inspection ratings for each defect in Table 3.

The PCI values for the two bridge structures were calculated in the CSIR STRUMAN BMS, based on the point cloud inspection ratings, to determine the condition categories of the structures. Table 4 presents the new PCI values and condition categories compared to the historic values as captured in the CSIR STRUMAN BMS.

It should be noted that the variance in the assigned defect ratings is a result of the different inspectors' interpretation of the defects. Higher or lower ratings do not necessarily imply that the defect has worsened over time or that maintenance had been done since the historic inspections. Consequentially, the new calculated PCI values for the two structures would differ from their historic PCI.

The inspectors were unable to inspect the abutment foundations, pier foundations and bearings of Bridge 1. Although the full details of the abutment seating crack were unclear from the images, the inspectors were still able to identify the defect, but a lower defect rating was assigned. The inspectors indicated that further on-site inspections are required to understand the full context of the defect. The new inspection methodology can thus be used as a screening process to determine if structures need further on-site inspections or not.

Bridge inspectors' comments and remarks

The bridge inspectors' comments and remarks were recorded during the point cloud inspections. This included limitations of the software and confidence in inspection ratings. The following remarks and comments were noted:

- The inspectors required dimensions of the bridges, including an indication of the scale and slope. They were unable to determine the flow direction of the river for Bridge 2.
- The software should indicate the orientation or angle from which images were taken. An image in the longitudinal direction of the bridges is required to determine the abutment and approach embankment settlement for Bridge 1 and Bridge 2.
- To improve the navigation of the point cloud model, a reset function is needed to return the model to the original orientation of the bridge.
- Images captured in the shadow of the bridge were difficult to inspect and the details on the images were unclear. The inspectors were unable to inspect the bearings of Bridge 1.
- The UAV pilot needs experience and training to ensure that all bridge elements are captured and to focus on important elements. Images should be captured from a closer distance to the bridge.
- Inspections would be easier if the flight path could be the same as the inspection sequence. This could improve the inspector's navigation of the point cloud model to complete inspection sheets systematically. The flight path could be specified by inspectors.
- The software requires a tool to label defects on the point cloud model for a more interactive inspection.
- Images could be grouped to create individual point cloud models of each bridge element for more detailed inspections.
- To use the software and to navigate through the point cloud models require training. After the inspectors completed the first bridge, they were more comfortable and accustomed to the process, and were able to inspect the second bridge with more ease and speed.
- The inspectors were able to determine with confidence whether a bridge requires further inspection or not. Bridge 1 had an abutment seating crack and the inspectors indicated that the bridge required a physical on-site inspection. They were confident when inspecting and rating the defects of Bridge 2, and did not see a need for further inspection.
- The inspectors indicated that they had lower confidence in the rating of defects using images only, and this resulted in more conservative (higher) defect ratings.
- Capturing inspection data electronically will be easier and safer using the new inspection methodology.

DISCUSSION OF RESULTS

The two bridge inspectors were able to inspect and complete inspection sheets for two bridge structures using the new proposed inspection methodology. The inspectors only used the point cloud models and the captured images during inspections.

The first bridge inspected was Bridge 1. Considering the newly completed inspection sheets, the inspectors identified and rated nine different defects. All the defects recorded on the historic inspection sheet were identified and an additional five defects were captured. The additional defects captured included a spall on the wing wall, debris on the deck surface, guardrails missing for pier protection, missing abutment drainage, blocked drainage, a blocked joint, damaged gland of the claw joint, and impact damage on the deck slab. The new defect ratings were similar when compared to the historic ratings for the defects that had been identified during both the new and the historic inspections. The slight variance in the ratings was subjective to the different inspectors' interpretation of the defects. The inspectors were unable to inspect the abutment foundations, pier foundations and bearings of the bridge. An image in the longitudinal direction of the bridge was required to confirm the foundation settlement. Although full details of the abutment seating crack were unclear from the images, the inspectors were still able to identify the defect. A lower rating was assigned to the defect compared to the historic rating and thus a higher PCI value was calculated for the structure. The inspectors recommended an on-site inspection for further investigation, as this defect was located on a critical element.

For the second structure, the inspectors were more comfortable with and accustomed to the new inspection methodology. Considering the newly completed inspection sheets for Bridge 2, the inspectors were able to identify and rate six different defects. The inspectors were able to identify two of the six defects recorded on the historic inspection sheet and captured an additional four defects. The additional defects that were captured included settlement of the approach embankments, guardrails not attached to the end blocks, a joint in need of a new asphalt plug, faded clearance signs and the missing structure number. The defects that were not captured during the inspection were debris and vegetation in the waterway, a crack in the abutment wall, corroded handrails, and a spall on a pier. The inspectors were able to inspect the waterway and handrails, but did not record any defects and were unable to determine the flow direction of the river. The inspectors were unable to identify from the images the 0.2 mm vertical crack in the abutment wall and the spall on one of the piers. The new defect ratings for the scupper defect were similar, compared to the historic ratings. There was a difference in the rating of the vegetation on the road surface hiding the guardrail defect. The historic inspection sheet indicated a higher degree rating compared to the point cloud inspections. The inspector on site could have perceived the defect to be more hazardous than the inspectors' interpretations from the images. The inspectors were confident regarding the inspection and defect ratings, and indicated that an on site inspection was not required.

Considering the new PCI values calculated for the two bridge structures, the structure conditions based on the point cloud inspection ratings for Bridge 1 were categorised as "good", and "very good" for Bridge 2. The condition of Bridge 1 was previously categorised as "fair". The difference in the categories is due to the abutment seating crack that had been rated higher during the traditional TMH 19 inspection. The defect is located on a critical structural element and has a higher priority weighting, contributing to the lower PCI value and condition category. The condition of Bridge 2 was previously categorised as "very good", which corresponded with the point cloud inspection ratings condition categories.

After the point cloud inspections, the inspectors could conclude whether further on-site inspections were needed. The new inspection methodology could thus possibly be used as a screening process for bridge inspections.

CONCLUSIONS

The proposed new inspection methodology has the potential to be a practical alternative to, or could form part of, traditional TMH 19 inspections in the future. Visual bridge inspections can be performed using only point cloud models and images – the inspectors were able to inspect structures and identify critical defects using the new inspection methodology. The point cloud models, as well as the captured images, provided sufficient detail for the inspectors to confidently inspect the majority of the bridge structure elements and rate defects accordingly.

The inspectors were able to identify all the defects that had been recorded on the historic inspection sheet for Bridge 1, while also capturing additional defects. For Bridge 2, not all the defects were identified during the inspection when compared to the historic inspection sheet. Defects such as a small crack and spall were omitted in their inspection. The inspectors were unable to inspect the pier foundations, abutment foundations and bearings. These limitations of the new inspection methodology could be improved by additional training of the UAV pilot to capture images of the bridge from a closer distance and to focus on critical bridge elements. In conclusion, the inspectors were nevertheless able to recommend whether the structure required further on-site inspection or not.

The proposed new inspection methodology could be used as a screening process for principal visual bridge inspections. Structures could be inspected using point cloud models and images to identify critical structures requiring further on-site inspection. This could reduce the number of structures that inspectors have to physically inspect and could enable them to only focus on the critical bridge elements when on site. The screening process could be performed by less experienced accredited bridge inspectors, while accredited senior bridge inspectors could perform quality control of the inspections.

The proposed new inspection methodology enables bridge inspectors to reassess a bridge within the five-year inspection period (before the next principal inspection is due) from the recently captured images and point cloud model, without having to schedule an on-site inspection. The bridge defects could be discussed with peers for different perspectives and provide additional input if required.

Bridge inspectors often prefer capturing inspections on paper-based sheets due to security risks on site. Inspection data then needs to be recaptured manually from the paper-based inspection sheets in the BMS once the inspector returns to the office. To manually recapture data is time-consuming and prone to human error. Using the new inspection methodology, inspection data can be captured electronically and automatically linked to the BMS.

The bridge inspectors raised important limitations regarding the practicality of the new inspection methodology. These comments included the quality of the images and the functionality of the software. Several images were captured from too far away, resulting in detail in these images being unclear. As the UAV pilot did not focus on all the critical bridge elements, images captured underneath the bridge were too dark, and the inspectors were also unable to determine the scale of the structure and the slope. These limitations need to be considered to improve the new inspection methodology and the credibility of inspections.

RECOMMENDATIONS FOR FUTURE WORK

The new inspection methodology proved to be valuable in concept but has limitations in practice. The inspectors' comments and remarks recorded during this study should be considered to improve the methodology. Images should be captured at a closer distance to the bridge structure. The UAV pilot should receive additional training to focus on critical bridge elements and to ensure that sufficient images are captured during the UAV flight path. The addition of a light to the UAV should be investigated to improve the quality of images captured in the shadow part of a bridge. Additional tools and features could be developed for software to improve the navigation of point cloud models. Functions such as labelling defects and measuring dimensions could enhance the inspector's interactive experience during the inspections.

The storage of data and images also needs consideration. Currently, the STRUMAN BMS makes provision for 17 typical inventory images and the number of defect images captured during an inspection, as prescribed in TMH 19 (COTO 2020a). The point cloud models that were created comprised approximately 450 images for the large bridge structures and 350 images for the medium bridge structures. If image data to create point cloud models are captured for an entire network of structures, the images will need to be stored on cloud-based platforms. Preselecting images to create point cloud models with fewer images could potentially reduce the required storage space and computation time to process the images.

The cost and time components of the new inspection methodology and traditional TMH 19 inspections also need to be considered and compared to determine if the new inspection methodology has cost- or time-saving benefits. The time- and cost-saving aspects of the new inspection methodology will depend on limiting the human involvement in inspections. This could be possible if deep-learning models could be developed to identify defects autonomously.

REFERENCES

Ciampa, E, De Vito, L & Pecce, M R 2019. Practical issues on the use of drones for construction inspections. *Journal of Physics: Conference Series*. Milan, Italy: IOP Publishing. Available at: **https://iopscience.iop.org/article/10.1088/1742-6596/1249/1/012016/meta**.

COTO (Committee of Transport Officials) 2020a. *TMH 19. Manual for the Visual Assessment of Road Structures. Part A: Road Structure Management Information.* Pretoria: SANRAL.

COTO 2020b. *TMH 19. Manual for the Visual Assessment of Road Structures. Part B: Visual Assessment Guide.* Pretoria: SANRAL.

Hallermann, N, Taraben, J & Morgenthal, G 2018. BIM-related workflow for an image-based deformation monitoring of bridges. *Proceedings*, 9th International Conference on Bridge Maintenance, Safety and Management, 9–13 July 2018, Melbourne, Australia.

Jahanshahi, M R, Kelly, J S, Masri, S F & Gaurav, S 2009. A survey and evaluation of promising approaches for automatic image-based. *Structure and Infrastructure Engineering*, 5(6): 455–486.

Kemp, L, Roux, M P, Kemp, M & Kock, R 2021. Application of drones and image processing for bridge inspections. *Proceedings*, 39th Southern African Transport Conference, 5–8 July 2021, Pretoria.

Kruger, E J & Nyokana, A A 2018. Bridge management implemented by the South African National Roads Agency. *Proceedings*, 9th International Conference on Bridge Maintenance, Safety and Management, 9–13 July 2018, Melbourne, Australia, pp 206–213.

Nordengen, P A & Nell, A J 2005. Development and implementation of a bridge management system for the provincial government of the Western Cape, South Africa. *Proceedings*, 5th International Conference on Bridge Management, Guildford, UK.

Perry, B J, Guo, Y, Atadero, R & Van de Lindt, J W 2020. Streamlined bridge inspection system utilizing unmanned aerial vehicles (UAVs) and machine learning. *Measurement*, 164. DOI:10.1016/j.measurement.2020.108048.

PIARC (Permanent International Association of Road Congresses) 2018. *The Use of Unmanned Aerial Systems to Remotely Collect Data for Road Infrastructure.* Special Project Report. PIARC Ref 2018SP03. Paris, France: World Road Association and Rednoa Inc.

SACAA (South African Civil Aviation Authority) 2017. *Remote Piloted Aircraft Systems.* Available at: **http://www.caa.co.za/Pages/RPAS/Remotely%20Piloted%20Aircraft%20Systems.aspx#** (accessed on 10 January 2021).

Wells, J & Lovelace, B 2018. *Improving the Quality of Bridge Inspections Using Unmanned Aircraft Systems (UAS).* Saint Paul, MN: Minnesota Department of Transport.