The feasibility of using commercially available Remotely Piloted Aircraft for network level visual inspection activities on provincial structures in the Western Cape

by

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Thesis presented in fulfilment of the requirements for the degree of Master of Engineering in Civil Engineering in the Faculty of Engineering at Stellenbosch University

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December 2021

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Abstract

The Department of Transport and Public Works (DTPW) of the Western Cape is accountable for effectively managing its bridges on a network level. The role comprises routine principal and safety inspections in accordance with the Technical Methods for Highways (TMH) 19 and the Construction Regulation (CR) 2014. Although the TMH19 human-based inspection methods are effective in detecting defects and identifying complex failure modes, the approach is resource intensive, time consuming, costly, dangerous at times and may yield subjective results. In addition, the DTPW has been unable to meet the safety inspection requirements of the CR2014 due to limited resources, lack of official safety inspection guidelines, and the needed high frequency of inspections.

Utilising Remotely Piloted Aircraft (RPA) for bridge inspections has been widely researched and promoted as a feasible alternative to conventional human-based inspection methods. RPA technology has the potential to increase the quality of data, decrease time spent on site and mitigate safety risks while fulfilling mandatory inspections and legal compliance. Using RPAs for bridge inspections has been successfully implemented in many countries. However, despite their potential RPAs are rarely used for bridge inspection activities in the Western Cape Province of South Africa.

Alternative approaches are proposed to address shortcomings in the TMH19 human-based inspection practices and to meet the CR2014 safety inspection requirements. These approaches include leveraging off-the-shelf RPAs and photogrammetric technology to create photo-realistic 3D digital models for extracting inventory data more effectively and to perform virtual safety inspections. The feasibility of these approaches was demonstrated through RPA test flights at two bridge sites. The findings were validated against the 2019 Principal Bridge Inspections information.

Utilising off-the-shelf RPAs and manually extracting data from photo-realistic digital 3D models eliminated the need to transfer data from on-site paper notes to a digital platform while also meeting all the TMH19 inventory requirements.

An off-site, computer-based visual bridge safety inspection was performed to determine whether the structure was fit for its intended design purpose and safe for continued use as required in terms of CR2014. It was shown that the condition information could be manually evaluated with little effort, and that the extracted information was sufficient to be used for a high-level visual assessment. The virtual inspection eliminates the need for field notes, mitigates gross mistakes and makes it unlikely that any detail of importance is omitted.

Opsomming

Die Departement van Vervoer en Openbare Werke van die Wes-Kaap is verantwoordelik om hulle brûe op netwerkvlak effektief te bestuur. Die rol behels hoof- en veiligheidsinspeksies volgens die Tegniese Metodes vir Hoofweë 19 (TMH19) en die Konstruksieregulasies 2014 (CR2014) op ‘n roetine basis. Alhoewel die TMH19 inspeksiemetodes effektief is in die indentifisering van foute en ingewikkelde maniere van swigting, is dit steeds hulpbronintensief, tydrowend, duur, soms gevaarlik en kan subjektiewe resultate lewer. Saam met dit kon die Departement nie aan die veiligheidsinspeksie vereistes van die CR2014 voldoen nie weens beperkte hulpbronne, die gebrek aan amptelike veiligheidsinspeksieriglyne en die hoë inspeksie frekwensie wat nodig is.

Die gebruik van afstandsbeheerde vliegtuie vir bruginspeksies is al baie ondersoek en aanbeveel as 'n haalbare alternatief vir konvensionele inspeksiemetodes wat fisies deur bruginspekteurs uitgevoer word. Afstandbeheerde vliegtuigtegnologie het die potensiaal om die kwaliteit van data te verbeter, die tyd wat op die terrein spandeer word asook die veiligheidsrisiko's te verminder, dit alles terwyl verpligte inspeksies en wetlike vereistes nagekom word. Die gebruik van afstandsbeheerde vliegtuie vir bruginspeksies is al in baie lande suksesvol geïmplementeer. Afstandsbeheerde vliegtuie word egter selde vir bruginspeksies in die Wes-Kaap Provinsie van Suid -Afrika gebruik, ondanks die potensiaal daarvan.

Alternatiewe benaderings word voorgestel om die tekortkominge in die TMH19 inspeksiepraktyke aan te spreek en om aan die CR2014 veiligheidsinspeksie vereistes te voldoen. Hierdie benaderings sluit die gebruik van afstandsbeheerde vliegtuie wat van-die-rak-af beskikbaar is, asook fotogrammetriese tegnologie om foto-realistiese driedimensionele (3D) modelle te skep. Die modelle kan gebruik word om relevante data meer effektief te onttrek en om virtuele veiligheidsinspeksies uit te voer. Die haalbaarheid van hierdie benaderings is deur middel van toetsvlugte by twee brûe gedemonstreer. Die 2019 provinsiale hoofbruginspeksie data is gebruik om die resultate te evalueer en te kontroleer.

Deur gebruik te maak van afstandsbeheerde vliegtuie en om fisies data van die foto-realistiese digitale 3D modelle te ontrek word die gebruik en oorskryf van papiernotas op 'n digitale platform oorbodig. Hierdie benadering voldoen ook aan al die TMH19 vereistes.

‘n 3D model was ook geskep en gebruik om ‘n rekenaarbaseerde visuele brugveiligheidsinspeksie uit te voer. Die doel was om vas te stel of die struktuur geskik en veilig vir gebruik is volgens CR2014, deur slegs gebruik te maak van die model. Die benadering was voldoende om die brug se kondisie met min moeite te evalueer. Die virtuele inspeksie elimineer die gebruik van handgeskrewe notas, verlaag moontlike foute asook die waarskynlikheid dat enige belangrike inligting weggelaat word.

Acknowledgements

I would like to express my appreciation to my employer, supervisor, family and wife. Without their support and guidance, the successful completion of my research would have been impossible:

My employer, the Department of Transport and Public Works of the Western Cape. Thank you for the bursary and the continued support throughout my studies.

My supervisor, Mr Chris Jurgens, who gave me the opportunity for further studies. Thank you for your technical guidance and mentoring that gave me clarity and understanding to complete the research. Your knowledge in the field of engineering and technology is truly exceptional and inspiring.

My parents, Johan & Karin Neethling and Danny & Sheila Macario. Thank you for your continued prayers, support, encouragement and love. Thank you for the environment you created that allowed me to pursue all my endeavours.

My supportive and lovely wife, Robina. Thank you for your faith in Christ, unconditional love, support and bottomless cups of tea.

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List of Abbreviations

2D	Two Dimensional
3D	Three Dimensional
AASHTO	American Association of State Highway and Transportation Officials
AI	Artificial Intelligence
BIM	Building Information Modeling
BMS	Bridge Management System
BrIM	Bridge Information Modelling
B-VLOS	Beyond Visual Line of Sight
COTO	Committee of Transport Officials
COVID	Coronavirus Disease
CR2014	Construction Regulations 2014
DJI	Da-Jiang Innovations
DTPW	Department of Transport and Public Works
FAA	Federal Aviation Authority
FHWA	Federal Highway Administration
FPV	First Person View
GPS	Global Positioning System
GPU	Graphics Processing Unit
HD	High Definition
ICAO	International Civil Aviation Organisation
JPEG	Joint Photographic Experts Group
KML	Keyhole Markup Language
MB	Megabytes
MDB	Microsoft Access Database
MP	Mega Pixel
OHSA	Occupational Health and Safety Act
PCI	Priority Condition Index
pdf	Portable Document Format
QC	Quality Control
RAM	Random Access Memory
RAMP	Road Asset Management Plan
ROC	Remote Operator Certificate
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
RPL	Remote Pilot Licence
SACAA	South African Civil Aviation Authority
SANRAL	South African National Road Agency Limited
SIP	Strategic Inspection Plan
SSD	Solid State Drive

TMH19	Technical Methods for Highways 19 - Manual for Visual Assessment of Road Structures – Part A: Road Structure Management Information
TMH22	Technical Methods for Highways 22 - Road Asset Management Manual
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UBIU	Under-Bridge Inspection Unit
WCG	Western Cape Government

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1 Introduction

1.1 Subject

This study investigates the feasibility of using commercially available, off-the-shelf, Remotely Piloted Aircraft (RPA) to increase the efficiency of network level visual inspection activities for bridges and major culverts for the Department of Transport and Public Works of the Western Cape Government.

1.2 Background and problem statement

Bridges and major culverts are essential transportation infrastructure because of their function to provide safe passage for people, animals, utilities and freight over rivers, roads or other difficult terrain. The planning, design, construction, maintenance and replacement of bridges and major culverts represent large capital investments for any national, provincial or municipal road and rail authority.

Public safety and cost implications are concerns which place major risk and liability on authorities should these structures not remain fit for their required purpose. To mitigate these risks, road and rail authorities must regularly conduct visual inspections and collect inventory data of structures in accordance with regulatory requirements (see Section 2.3.1). Any person who fails to comply with the provisions of the Occupational Health and Safety Act (OHSA) is guilty of an offence and liable upon conviction to a fine or imprisonment.

Visual inspections form the basis of a Bridge Management System (BMS) and are important for the collection of inventory data, condition assessment of structures and rendering structures safe for continued use. However, visual inspections are often expensive, time consuming and dangerous for the inspector. According to Gillins, Parrish, Gillins and Simpson (2018), under-bridge inspection units, temporary scaffolding, boats and rope access are often required to inspect bridge elements. Making use of these equipment and methods can be costly and dangerous to the inspectors and road users, especially when accommodation of traffic is required for road or lane closures.

According to the Road Asset Management Plan (RAMP) for 2020/21 to 2029/30 of the Department of Transport and Public Works (DTPW) of the Western Cape, the latest network level principal inspections of approximately 2800 bridges and major culverts were completed in 2019 (RAMP, 2020). Before this they were completed in 2003 (Nell, Newmark & Nordengen, 2008). The frequency of inspections is therefore in contravention of the provisions of the TMH19 (see Table 2.3).

Other road authorities in South Africa are similarly aware of and concerned about the condition of their bridges and major culverts following recent bridge collapses. A pedestrian bridge spanning over the Old Vereeniging Road close to Angus Station in Alrode South, Alberton, collapsed on a truck without warning on 4 July 2020 (OFM, 2020). According to a media release on 09 November 2017 by the Johannesburg Roads Agency, 37 of its bridges had collapsed during the rainy seasons since 2013 (Johannesburg Roads Agency, 2017).

South Africa is not the only country experiencing failing road infrastructure. On 30 September 2006, the deck of a road-over-road bridge in Laval, Canada collapsed without warning, killing five people (Johnson, Couture & Nicolet, 2007). On 14 August 2018, a section (about 243 m) of the viaduct and one of the piers of the Morandi Bridge in Genoa, Italy collapsed. The tragedy resulted in the death of

43 people (Calvi, Moratti, O'Reilly, Scattarreggia, Monteiro, Malomo, Calvi & Pinho, 2019). Unfortunately, Zordan (2018) found more than 10 other cases of bridge collapses in Italy since 2007.

In their study, Calvi *et al.* (2019) established that bridge failures were primarily due to:

a) Natural or human-induced catastrophes (earthquakes, major impacts, etc.)
b) Fatigue and/or deterioration (corrosion, carbonation, etc.) in conjunction with higher/heavier traffic loading
c) Poor and/or inadequate designs
d) Poor and/or inadequate construction
e) A combination of some or all of the above.

Authorities and/or bridge inspectors can mitigate the risk of failing infrastructure through correct decisions and actions which are based on accurate bridge data. The required data stem from visual inspections (Rashidi & Gibson, 2012).

A need therefore exists to develop efficient, safe and cost-effective methods to obtain current inventory and condition data whilst adhering to the required regulations. This will assist authorities to have an updated BMS and make critical and technical decisions with circumspection. Due to the rapid advancement of commercially available RPAs, an alternative and innovative approach is envisaged for future bridge inspection activities on a network level.

With limited South African peer-reviewed literature available regarding the use of RPAs for visual bridge inspection activities, it appears that this technology is in its infancy in South Africa. Therefore, RPA test flights are important to evaluate this technology's boundaries in terms of its capabilities and limitations before regarding RPAs as feasible for visual bridge inspection activities on the provincial road network of the Western Cape.

1.3 Aim and objectives

The aim of this study is to increase the quality of and decrease the time spent on overall visual inspection processes to fulfil mandatory inspections and legal compliance in the Western Cape, South Africa through investigating RPAs for bridge inspection activities on a network level. Based on this aim, the following objectives are identified:

- Understand applicable standards and regulations to use RPAs for bridge inspections in SA (SACAA, CR2014, TMH19)
- Identify aspects of conventional human-based visual inspections that are time consuming, costly and/or dangerous or hinder the quality of data
- Investigate the feasibility of utilising RPAs and photogrammetric technology to obtain inventory data on a network level for principal bridge inspections
- Investigate the feasibility of utilising RPAs and photogrammetric technology for off-site safety inspections on a network level.

1.4 Scope and limitations

The current uses of RPA technology for bridge inspection activities are investigated in this study. The scope of the study involves provincial bridges as classified in the TMH19 restricted to the Western Cape region of South Africa. If proven that the use of RPAs for visual bridge inspection activities is feasible on a network level in the Western Cape, it is reasonable to expect that it would be feasible for the other provinces in South Africa.

Network level inspection data deal with the bridge stock on the road network as a whole and is typically concerned with high-level assessments in terms of condition, planning and budgeting, whilst adhering to the provisions of regulations and policies.

Project level inspections cover specific structures within the road network and are typically concerned with in-depth detail relating to their condition and immediate action required e.g., replacement options, rehabilitations options, detailed quantities and costing and design alternatives. They typically include additional types of assessments such as non-destructive testing, sounding surveys and load testing. Project level inspections are beyond the scope of this study, which focuses only on network level inspections (see Section 2.3.3).

The TMH19 distinguishes between three types of network level visual inspections - principal, partial and completion inspections. These inspections must be performed by an accredited bridge and/or culvert inspector. In addition, the CR2014 requires a safety inspection performed by a competent person, i.e., a suitable technical person. Principal and safety inspections are conducted periodically, while partial and completion inspections are conducted once-off or as required. Partial, completion and safety inspections have less stringent requirements than principal inspections but are similar in approach and execution. Therefore, if RPAs are shown to be feasible for obtaining inventory data as required for principal inspections, it is assumed that they will also be feasible for the other types of inspections.

The specific characteristics and technical capabilities of a suitable RPA to perform bridge inspection activities were based on a wide-ranging literature review, the provisions of the South African Civil Aviation Authority (SACAA) regulations and CR2014, as well as RPA test flights to meet the outcomes as prescribed in TMH19. The feasibility of using RPAs with respect to supply chain procurement processes and the future implementation for the WCG DTPW and other road authorities are also considered.

The study was limited to visual inspection activities on a network level. Therefore, only commercially available, off-the-shelf RPAs with no special alterations or modifications were considered. Furthermore, the only payloads were the standard digital cameras fitted to the RPA during manufacturing.

With an increased use of RPAs in South Africa, the SACAA regulations for RPAs have been devised to ensure safe operation without invading privacy or posing a threat to the public, protected areas and infrastructure. As a result, RPA operations are subject to specific restrictions. The bridge sites where RPA test flights took place were selected to be outside the SACAA no-fly zones and areas where approval was required from the Director of SACAA.

1.5 Research methodology

The outcomes of this study are based on a literature review, observations of principal inspections, interviews with industry specialists and test flights using RPAs for bridge inspection activities.

The literature review synthesises locally and internationally published literature, which allows for the identification of common uses, limitations, benefits and applications of RPAs for bridge inspection activities.

Accredited inspectors (structural engineers, technologists and technicians) were observed during routine bridge and major culvert principal inspections. Inspectors were then interviewed to identify ways and means of improving existing inspection methods by using RPAs. South African Remote Pilot Licence (RPL) holders were also interviewed to assess the current RPA market and demand in South Africa and specifically in the Western Cape. The interviews comprised 11 explorative and open-ended questions, as well as two questions that were used for statistical purposes.

Using RPAs to develop photorealistic 3D models for extracting inventory photographs and data according to the TMH19 requirements was investigated. The practicality and effectiveness of this approach was evaluated against the conventional inspection methods.

1.6 Overview of thesis research phases

The research study consists of three main phases, as shown in Figure 1.1. Each phase is described and outlined in Sections 1.6.1 to 1.6.3.

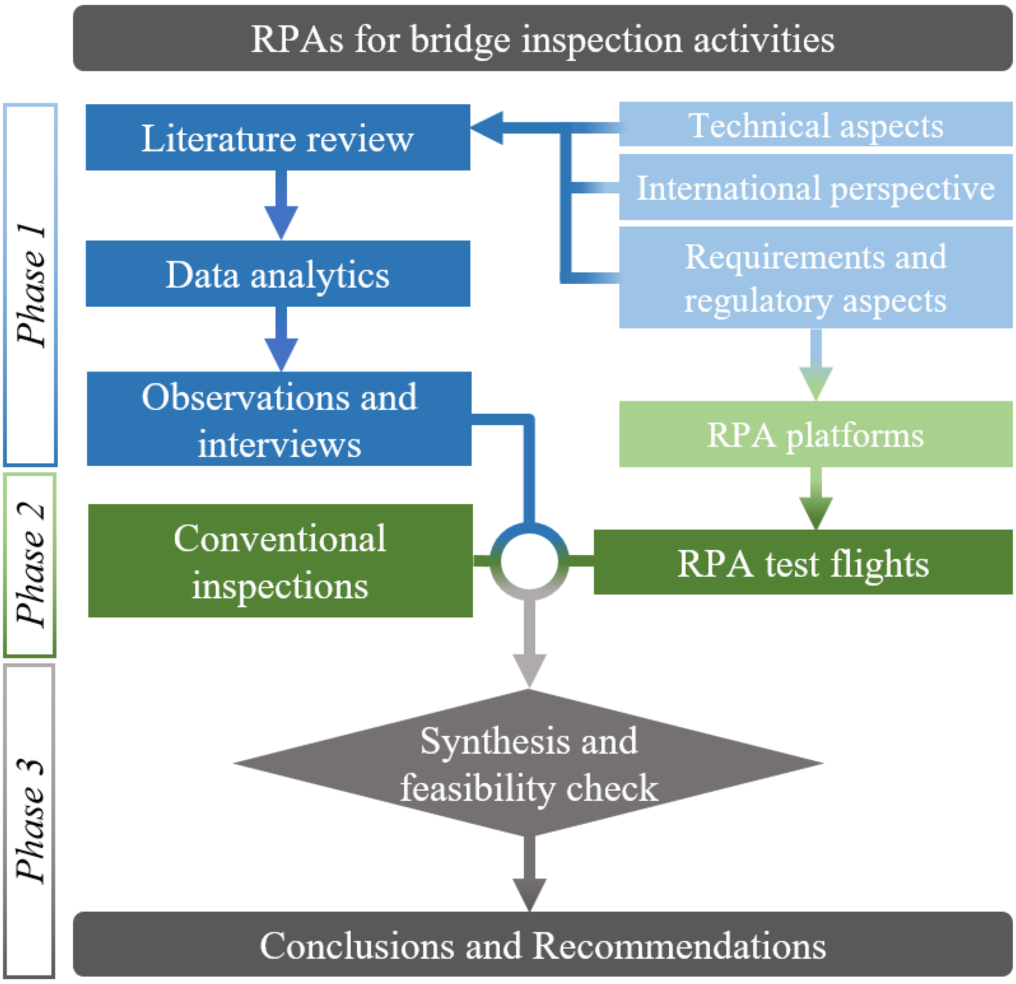


Figure 1.1 Plan of development for this research study.

1.6.1 Phase 1: Literature review, analysis of the 2019 bridge inspection data, observations and interviews

A literature review was conducted to provide an overview of RPAs and their use in the engineering environment, specifically relating to visual inspection activities for road bridge structures. Aspects such as appropriate types of RPAs for inspections, South African regulations applicable to RPAs and other key findings were included in the review.

Observations of actual principal inspections during 2019 were conducted to develop an understanding of current principal bridge inspection methods.

Interviews were held with accredited inspectors from engineering consulting firms in the Western Cape to determine whether they had made use of RPAs for bridge inspection activities. The interview questions were twofold. If inspectors had made use of RPAs, their experience, outcomes and key observations and opinions were surveyed. If they had not made use of RPAs for bridge inspection activities, the reasons for their decision were explored. Interviews were also conducted with RPL pilots to determine the current use of and demand for RPAs in the engineering industry in the Western Cape as well as in South Africa. The interview questions aimed to capture their opinions and/or experience of using RPAs for bridge inspection activities.

After having developed a holistic understanding of RPA technology and conventional visual inspections based on the literature review, observations and interviews, the Western Cape Government's 2019 bridge inspection data were analysed. The purpose of the analysis was to establish where and how RPAs could be incorporated into future network level visual assessments.

1.6.2 Phase 2: The development of alternative and optimised approaches to obtain inventory data using RPA technology

RPA test flights were undertaken to determine the advantages, disadvantages and limitations of using off-the-shelf, commercially available RPAs for bridge inspections, specifically focusing on obtaining inventory data. The equipment, methodology, SACAA legal compliance and operational workflow are described as part of this phase. Two bridge sites were selected for this study.

The two bridge sites were used to compare conventional human-based inspections with the alternative and innovative approach of using an RPA to assist with inspection activities. The research at these sites included a detailed investigation of current work practices during an actual routine inspection for WCG DTPW and how RPAs could be incorporated into the process. The primary focus was to investigate an alternative approach of obtaining inventory data as well as data for performing virtual safety assessments.

The post-processing of the data was evaluated against the requirements for safety inspections to ascertain if the same data could be used to determine safety conditions and requirements needed to comply with regulations.

1.6.3 Phase 3: Synthesis of research, feasibility of RPAs, recommendations and conclusions

Synthesis of the findings in Phases 1 and 2 formed the basis of the feasibility assessment of using RPAs for bridge inspection activities on the provincial road network of the Western Cape.

The unprocessed data of the interviews are included in the appendices. The processed data were integrated into the recommendations and conclusions of the final chapters.

2 Literature review

The chapter covers the following:

- The definition of Remotely Piloted Aircraft (RPA)
- An international perspective of utilising RPAs for bridge inspection activities
- Current bridge management and visual inspection practices in South Africa and possible bridge inspection activities suited for RPA-based inspections
- An overview of the legal and regulatory requirements in effect under the South African Civil Aviation Authority when making use of an RPA
- Synthesis of the findings, validation of the aim and objectives and identification of gaps in the current literature.

2.1 What is an RPA?

An RPA is defined by the South African Civil Aviation Authority (SACAA) as an unmanned aircraft that can be flown without a pilot physically on board throughout the flight. Several different terms are used in the industry and in published literature to describe unmanned aircraft. These terms are used interchangeably and typically include drones, unmanned aerial vehicles (UAVs) and small unmanned aircraft. The terminology used throughout this thesis, wherever possible, is aligned with the definitions and descriptions of the SACAA.

An RPA can either be controlled from the ground by a remote pilot or pre-programmed to fly autonomously. The RPA is managed through command-and-control links by a remote pilot from a remote pilot station. Collectively this is referred to as a remotely piloted aircraft system (RPAS). The term RPAS is also used by the International Civil Aviation Organization (ICAO) and the Canadian Aviation Regulations and Standards of Transport Canada.

International equivalent authorities such as the Federal Aviation Authority (FAA) of the United States of America define an unmanned aircraft, including all the components and communication links, as an unmanned aircraft system (UAS). Table 2.1 shows the basic components of an RPAS along with FAA equivalent terms that refer to the same basic components of the system. The RPAS components are discussed in Chapter 6.

Table 2.1 Basic components of an RPAS in terms of SACAA and FAA.

Basic RPAS components in terms of SACAA	Equivalent basic UAS components in terms of FAA
Remotely Piloted Aircraft (RPA)	Unmanned Aircraft
Remote Pilot	Human Operator
Remote Pilot Station	Ground Control Station
Payloads	Payloads

2.2 International perspectives on utilising RPAs for bridge inspection activities

In recent years there have been significant development and improvement in commercially available RPAs and subsequently more resources have been invested in researching this technology for bridge inspections (Tomiczek, Whitley, Bridge & Ifju, 2019). RPA technology has matured rapidly and has become readily available to the general public with a variety of options in terms of performance, type, size, affordability and user-friendliness (Zink & Lovelace, 2015).

Several studies have been conducted to investigate the use of RPAs for bridge inspection purposes. Dorafshan and Maguire (2018) found that more than 30 departments of transportation in the United States of America had utilised commercially available RPAs for inspection purposes, either for research purposes or in practice. However, a survey by the American Association of State Highway and Transportation Officials showed that the road authorities were not convinced that RPAs could be used as an effective tool to assist with bridge inspections (Wilson, 2018). To address shortcomings and challenges posed by conventional inspection methods, new approaches and technologies need to be investigated while at the same time providing reliable data (Feroz & Dabous, 2021).

2.2.1 Advancements in RPA technology

Hallermann and Morgenthal (2014) researched how RPAs could simplify the inspection of critical structural elements on bridges. They developed a method to obtain inspection data in a semi-autonomous manner using GPS-coordinated flight missions. The method was tested on a large arch bridge by recording high-definition videos of the deck, spandrel walls and arch where an under-bridge inspection unit (UBIU), rope access, scaffolding or special hoisted platforms would typically have been required.

Despite using professional, advanced and high-end RPAs for their study, significant technology limitations were identified which confined the use of this technology for bridge inspection activities. These limitations included small payloads that restricted the types of cameras that can be used. The biggest existing challenges experienced during the test flights were high wind speeds, changes in natural lighting and autonomous flight issues specifically related to the loss of Global Positioning System (GPS) signals. Similarly, Gillins *et al.* (2018) and Tomiczek *et al.* (2019) found that wind conditions were the most important limiting factor to consider when operating an RPA in close proximity to a bridge. In addition, the sun angle, visibility (i.e., low light), cloud coverage and correct camera settings were deemed critical factors that affected the quality of imagery.

There have been continuous advancements in camera and sensor technology; these now enable RPAs to use visual navigation systems to fly in areas and hover in-place where GPS signal is weak or absent. RPA pilots are able to safely navigate and capture high-resolution video and photographs with improved image quality in difficult terrain and hard-to-reach areas (Perry, 2019). However, Tomiczek *et al.* (2019) found that the flight navigation and control technology still required improvement and refinement, specifically for RPA flights underneath bridge decks, i.e., in GPS-denied and low light areas.

2.2.2 RPAs as a supplementary tool to current bridge inspection practices

Gillins *et al.* (2018) evaluated the performance of RPA-assisted bridge inspections to determine how this technology could be incorporated into current visual inspection practices to reduce costs and enhance safety features. Their study mainly focused on the use of RPAs as a supplementary tool to identify defects and determine the condition of bridges. Their study did not include autonomous or semi-autonomous methods to obtain data. They found that the use of RPAs satisfied numerous requirements of initial and routine inspections but was not beneficial for project-level inspections. Despite a 30% increase in office time due to flight planning, additional post-processing and data analysis, they estimated savings of approximately $10 000 per bridge inspection where an RPA was suitable for use. The high-level cost saving was mainly based on reduced access-equipment rental and traffic control costs. The use of UBIUs typically requires complete road closures or long durations of traffic accommodation as opposed to RPAs which require only short traffic accommodation intervals, if any (Darby, Hollerman & Miller, 2019).

Tomiczek *et al.* (2019) and Feroz and Dabous (2021) reported similar findings in terms of key advantages of integrating RPAs into current bridge inspection practices. These included possible cost savings and improved accessibility by removing the need for traffic accommodation and a UBIU when inspecting bridges. RPAs could be utilised rapidly when special and damage inspections were required. Although Gillins *et al.* (2018) also found that RPAs were very useful for special inspections, their research showed that they had limited use for damage inspections where physical contact (i.e., "hands-on") with the structure is required e.g., physically probing, scarping or performing an impact sounding test with a hammer. Both studies showed that RPAs had limited use for fracture-critical inspections.

Darby, Hollerman and Miller (2019) investigated the feasibility, practical uses, advantages and disadvantages of RPA-assisted bridge inspections in terms of their efficiency and safety. Their study found that RPAs should be considered mainly as a tool to assist bridge inspectors when hands-on inspections were not required. This would increase the safety of the inspectors and the public. For example, some bridge components such as piers or pylons are out of reach to mobile cranes and require dangerous access methods for visual inspections; RPAs can complete the same task with much less risk and cost. They recommended that RPAs should be used during emergency and routine inspections to effectively obtain visual information without using expensive or dangerous access methods. The quality of photographs taken of bridge components on semi-autonomous and pre-programmed RPA flights at specified spatial intervals (i.e., equidistant points) was much higher than that of photographs taken by an inspector.

In a similar study, Seo, Wacker and Duque (2018) investigated the limitations and capabilities of RPA technology as an aid to bridge inspectors by conducting a detailed comparison between conventional bridge inspections and RPA-assisted bridge inspections. Their study was limited to bridge inspection activities in terms of image quality and damage detection. The inspectors were able to detect several defects on different structural components using photographs that were captured by the RPA. Similar to Gillins *et al.* (2018), their study found that image processing software using high-resolution photographs was an effective approach to manually identify and quantify structural and cosmetic defects on various bridge components. Photogrammetry models were developed using the captured data which allowed the reviewers to conduct further detailed manual evaluations of the identified defects.

The study showed that RPAs could be used to effectively capture photographs of defects and accurately quantify specific damages. However, the study did not offer an automated approach to data collection and analysis or a method to navigate through the photographic data. The inspectors were still required to manually process all the information to identify, and determine the condition of, the defects. Both studies found that RPA-assisted bridge inspections could save time on site by eliminating the need for expensive specialist access equipment and could acquire data faster, reduce costs and mitigate inspection risks.

These studies mainly focused on the RPAs' ability to capture imagery for post-detection of structural defects and did not elaborate on the work associated with the management of inventory data once obtained and analysed.

2.2.3 Automated bridge inspection systems utilising RPA technology

Xu and Turkan (2019) attempted to solve the inspection and associated data management problems by utilising RPAs, computer vision algorithms and Bridge Information Modelling (BrIM) for collecting, analysing, managing and storing the data. They were able to manually identify structural defects and automatically detect cracks using the high-resolution photographs captured by an RPA. By using BrIM in AutoDesk BIM 360 Glue, they developed 3D bridge models on Revit from 2D as-built drawings. They did not use photogrammetric technology. The 3D models were used to manually assign defects to the digital structural elements and formed the basis of an integrated model containing the historic bridge inspection data and RPA photographs. Creating the 3D model using the proposed manner was costly, time consuming and inefficient, and is not considered an implementable option for road authorities.

Perry, Guo, Atadero & Van de Lindt (2020) developed and tested a similar, but more advanced, streamlined inspection system to automatically identify the defect types, create 3D point cloud models using machine learning, and generate an elementwise as-built BrIM model to document and manage the bridge assessment information.

Notwithstanding the progress that has been made in software algorithms, machine learning and artificial intelligence to identify and quantify structural defects such as cracks, spalling and settlement, additional research is required for the software to automatically identify different bridge components (i.e., inspection items) and assign the defects to the components. Research has been done on vision-based bridge component recognition using multi-scale neural networks for bridge component recognition. Some success has been achieved for high-level recognition tasks. It is however too inaccurate and inconsistent at this stage for widespread use (Kim, Yoon & Sim, 2020; Narazaki, Hoskere, Hoang, & Spencer Jr., 2020). The ability to assign defects to identified components is especially important for South African network bridge inspections. Each bridge component carries a unique weighting to calculate the Priority Condition Index (PCI) for a structure (TMH22).

Although these studies showed significant progress in advanced data analytics tools, the research did not lead to any implementable, scalable, cost or time-saving solutions for network level bridge inspections. Furthermore, it was unclear whether the research was aimed at in-depth project level inspections or network level inspections. Network level bridge inspections refer to all the bridges on the road network and are typically concerned with high-level assessments in terms of condition, planning and budgeting, whilst adhering to the provisions of regulations and policies. The literature shows that RPA technology and associated analysis software is not mature enough for bridge inspections and condition analysis to be fully automated in terms of accuracy, consistency and reliability.

2.3 Overview of current bridge management and bridge inspection practices in South Africa

Nordengen and De Fleuriot (1998) found that road authorities in South Africa were investing more time and resources in maintaining existing road infrastructure, due to limited funds being available for new road construction. The study showed that high future maintenance costs can be reduced or mitigated by determining the optimum time to maintain structures at an acceptable serviceability level. In a similar study, Hallermann and Morgenthal (2014) found that effective strategies for monitoring important structures such as bridges are essential in terms of reaching and/or extending their design service life.

With limited funds available and long-term needs for bridge maintenance, rehabilitation and replacement strategies, government authorities require bridge information that is obtained from detailed, regular and continual inspections (Darby, Hollerman & Miller, 2019). Efficiency in this regard could be achieved through sustainable resource management, requiring the maintenance and monitoring of existing infrastructure through innovative methods. A systems approach is therefore needed to obtain data for effective structure management (Nordengen & De Fleuriot, 1998). Research by Perry (2019) pointed to the need to develop more time and cost-efficient inspection frameworks which could yield more consistent and quantitative results. With recent developments in RPA technology in terms of improved performance and affordability, a stream-lined systems approach could be achieved by leveraging this technology (Perry, 2019).

Sections 2.3.1 to 2.3.3 provide an overview of South Africa's legal mandate to inspect bridges and major culverts, a description of the Western Cape Government's current Bridge Management System (BMS) and a review of current bridge inspection activities. The objective was to identify aspects of South Africa's legal mandate to inspect structures and conventional bridge inspection processes that can be improved and/or replaced by using an RPA.

2.3.1 Legal mandate to inspect bridges and major culverts in South Africa

In South Africa the national, provincial and municipal road authorities are obligated to develop, maintain and protect public investments such as road infrastructure. This ensures continued safe-to-use and functional transportation infrastructure such as bridges and culverts on the road networks. The documents that outline the requirements and provisions for bridge and major culvert inspections are:

- The Technical Manual for Highways (TMH) 19 Committee Draft Standard 2019: Manual for the visual assessment of road structures (hereafter referred to as 'TMH19')
- The Construction Regulations (CR), 2014 of the Occupational Health and Safety Act (OHSA), 1993 (hereafter referred to as 'CR2014').

The TMH19 sets out South Africa's official requirements and uniform methods for obtaining inventory data and visual condition assessment data of road structures such as bridges, culverts, retaining walls and gantries. The data are captured and analysed on a bridge management system at a network level. The manual explains the procedure for visual inspections to ensure execution in a coherent manner across road authorities. It further describes the steps for road authorities and inspectors to follow when performing bridge inspections as well as the equipment and materials required; the need for additional inspections; quality assurance; and occupational health and safety requirements.

The CR2014 describes and explains the duties, responsibilities and obligations of clients, designers and contractors when undertaking construction and maintenance works. The CR2014 defines a structure, amongst other things, as any steel or reinforced concrete structure, any bridge, any structure retaining earth, or a designed structure to alter or preserve any natural feature. According to this definition, all bridges and culverts are considered a ‘structure’ and therefore all road authorities must comply with the provisions of the OHSA regulations where applicable.

2.3.2 Types and frequency of network level inspections

The TMH19 describes three types of inspections that must be carried out by accredited inspectors at a network level. These include:

- Principal inspections
- Partial inspections
- Completion inspections.

Principal inspections must be carried out every five years. When principal inspections cannot be fully completed due to the need for specialised access equipment such as an Under-Bridge Inspection Unit (UBIU), it is referred to as a partial inspection. Literature shows that using an RPA for bridge inspection activities could help mitigate partial inspections or the need for costly specialised access equipment (Darby, Hollerman & Miller, 2019).

Completion inspections are carried out after the completion of a new bridge, or a major culvert, or after rehabilitation/maintenance works, and take the form of principal or partial inspections (TMH19). If required, certain defects on a bridge should be monitored for further signs of deterioration. These monitoring inspections are typically carried out as required after floods, major disasters or monitoring of cracks (Nordengen & De Fleuriot, 1998).

The TMH19 further describes the structure types and definitions, inspection types and definitions, assessment methods and procedures, inventory data requirements and bridge inspector accreditation requirements for bridge and culvert inspectors (Appendix K).

The frequency of principal inspections in South Africa is slightly relaxed when compared to international equivalent inspections and regulations. For example, the federal regulations in the USA require bridge inspections and reporting to be conducted biennially in terms of Part 650, Subpart C, Sec. 650.305 of the National Bridge Inspection Standards (2004) provided in Title 23 of the Code of Federal Regulations, as opposed to every five years in South Africa.

The CR2014 states that structure owners (i.e., road authorities) must ensure that safety inspections are carried out once every six months for the first two years after the structure has been built and yearly thereafter. The inspections must be carried out by a person that is competent to render the structure safe for its intended design purpose and fit for continued use. The inspections as required by CR2014 are hereafter referred to as safety inspections. Safety inspections are high-level network inspections and there are no official guidelines or uniform methods to conduct these inspections in South Africa.

A summary of the frequency of bridge inspections according to TMH19 and CR2014 which is applicable to this research is presented in Table 2.2.

Table 2.2 Frequency required of visual bridge inspections according to technical manuals and regulations in South Africa.

Technical Manuals and Regulations	Frequency of inspections
TMH19	Principal inspections should be carried out every five years.
CR2014	Safety inspections should be carried out once every six months for the first two years and thereafter yearly.

2.3.3 Network level inspection data required for the Western Cape Government's Bridge Management System

Network level inspection data deal with the bridge stock on the road network as a whole and is typically concerned with high-level assessments in terms of condition, planning and budgeting whilst adhering to the provisions of regulations and policies. The Department of Transport and Public Works of the Western Cape uses the StrumanBMS Bridge Management System (BMS) to manage the network level inspection data (Nell, Newmark & Nordengen, 2008). StrumanBMS was developed around the TMH19 requirements and consists of several modules comprising inventory, inspection, condition, budget, assets value, and a summary of all the data. In addition, effective bridge management systems rely on updated inventory and inspection data obtained through visual inspection. Even though visual inspections are time consuming in terms of collecting and processing data, it remains the preferred method of conducting bridge inspections (Bolourian & Hammad, 2020).

The TMH19 defines several photographic views for each structure type to ensure consistency of inventory photographs. General, arch and cable bridges require 15 standard photographs plus photographs of any other salient feature. Cellular bridges and major culverts require eight standard photographs plus photographs of any other salient features. Each view has a standardised number, and all photographs must be geotagged. The positions (excluding viewpoints 12, 13 showing the bridge number) where the standard inventory photographs should be taken from are shown schematically in Figure 2.1.

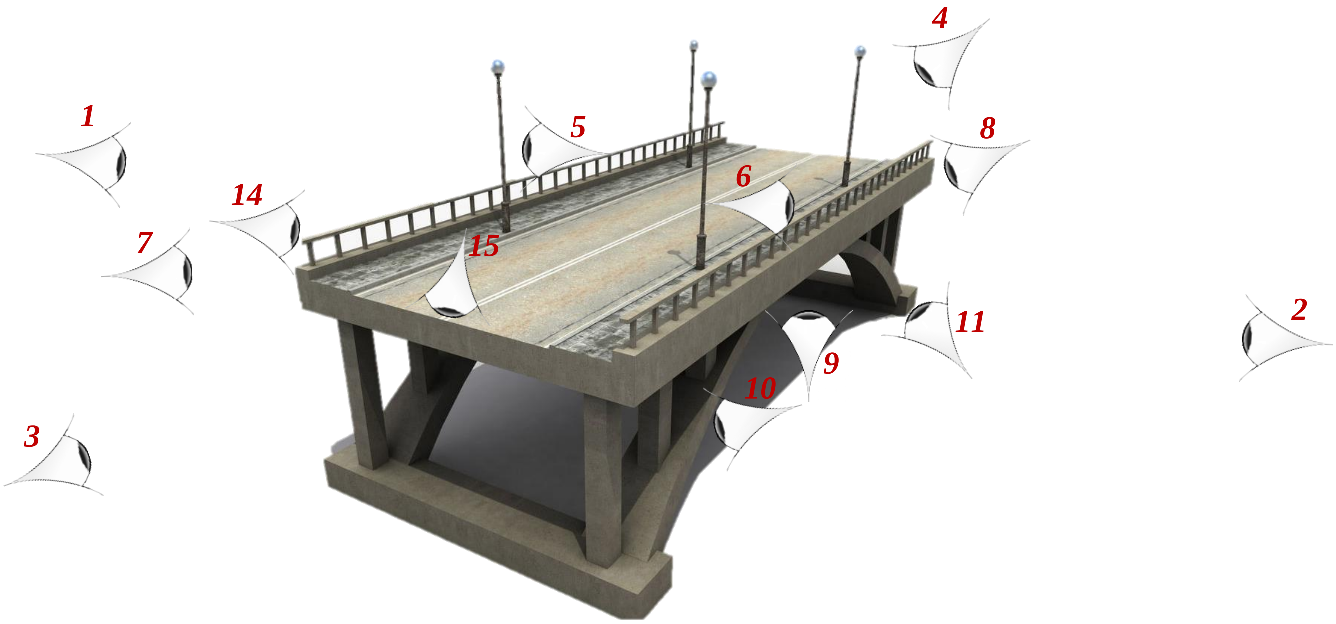


Figure 2.1 TMH19 standard inventory views for bridges.

Capturing inventory photographs and data appears to be a suitable activity for an RPA. As it is not required that inventory photographs and data are collected and processed by an accredited bridge inspector, they may be captured by any competent person. It is therefore possible to remove the acquisition of inventory data from principal inspections if a feasible alternative is available to obtain the required data.

The focus of this study is therefore on the StrumanBMS Inventory Module and the Inspection Module where the use of an RPA could contribute to improving the efficiency, cost, safety and quality of bridge inspection activities to obtain and capture relevant data. The information in the other modules is based on data obtained from the Inventory Module and Inspection Module and the content of each module is explained in detail by authors in the Development and Implementation of a Bridge Management System for South African Road and Rail Authorities (Nordengen & De Fleuriot, 1998).

Low investment costs are essential for RPAs to be considered on a network level. This is due to the large number of structures to be inspected periodically and the associated risk of RPA losses resulting from poor weather conditions, collisions, crashes, malfunctions and mechanical deterioration.

2.4 Legal and regulatory requirements in effect under the South African Civil Aviation Authority (SACAA)

The use of an RPA in South Africa is regulated by Part 101 of the Civil Aviation Regulations, 2011 as amended by GNR 40376 of 28 October 2016 and GNR 432 of 19 May 2017 with effect from 21 June 2017 (hereafter referred to as "Part 101"). The main function of Part 101 is to facilitate and regulate the use of an RPA in the South African airspace for commercial, corporate and non-profit organisations, and firms.

Table 2.3 shows a summary of the requirements and operational limitations for commercial, corporate and non-profit operations' applications in terms of Part 101 which are most pertinent to bridge inspections. As such, the summary is not comprehensive, and the RPA operator is still responsible to get acquainted with and comply with all the applicable and most recent provisions and requirements.

Table 2.3 Requirements and operational limitations for commercial, corporate and non-profit applications in terms of Part 101 relevant to bridge inspections.

Requirements and operational limitations	Provisions of Part 101
Operator and general requirements *(Part 101.04.1)*	The RPA must be registered, and the operator must have a valid: • Remote Pilot Licence (Multi-rotor); and a • Remotely piloted aircraft system Operators Certificate (ROC) with operations specification for commercial, corporate, and non-profit operations.
Weather conditions *(Part 101.05.1)*	RPAs may not be operated when weather conditions prevent the remote pilot from seeing the RPA whilst flying.
Beyond visual line of sight (B-VLOS) *(Part 101.05.11)*	RPAs may not be operated beyond visual-line-of-sight. Flights may only be conducted in visual meteorological conditions, below 121.92 m (400ft) above the ground. Wireless video streaming technology enables the remote pilot and flight crew to have live in-flight 'first-person view' of the surroundings and obstacles; however, this does not satisfy beyond visual line of sight (B-VLOS) requirements of Part 101. A special permit is required for B-VLOS operations which are outside the scope of this study.
Operations in the vicinity of people, public roads, and structures *(Parts 101.05.14 & 101.05.15)*	RPAs may not be operated in the following conditions: • Within a lateral distance of 50 meters or directly overhead a group of people or a person. • Over, adjacent to or within 50 meters from a public road. • Within a lateral distance of 50 meters of a building or structure.

The General Restrictions are included in Part 101.05.10 of the Civil Aviation Regulations and include the following conditions concerning where RPAs may not be operated:

- Above 121,92 m (400 ft) from the ground
- Within a radius of 10 km from an airport, helipad or airfield
- Within controlled/restricted/prohibited airspaces
- If the total weight (including the payload) is more than 7 kg.

No-fly zones include national parks and conservation areas, prisons, power plants, police stations, crime scenes and courthouses. All the no-fly zones in South Africa can be viewed on google maps by following the link below. An extract of the Cape Town area in the Western Cape is shown in Figure 2.2.

https://www.google.com/maps/d/u/0/viewer?mid=1dysv62Uj_lMC07jtE99-x8iRVNU&ll=-32.55596514645429%2C21.407696583234838&z=8

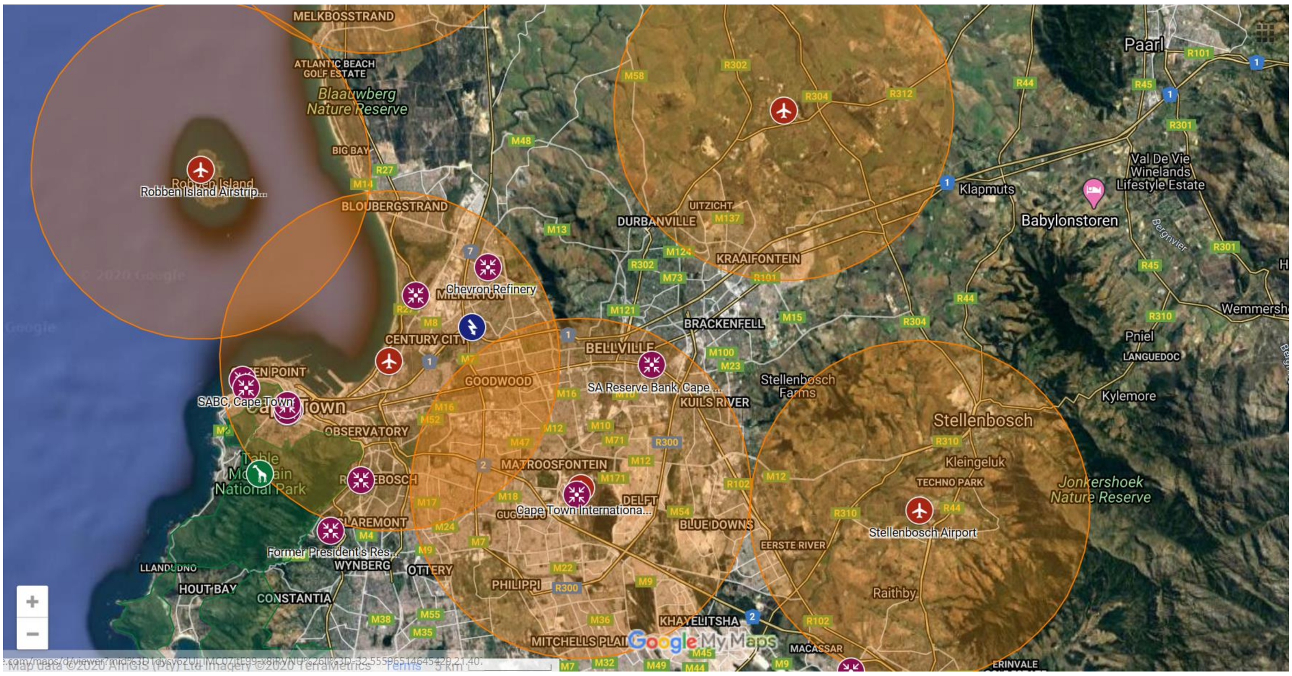


Figure 2.2 Example of no-fly zones in the Cape Town area of the Western Cape (image captured from ‘No Drones Zones South Africa’).

General restrictions and the provisions, conditions and restrictions highlighted in Table 2.3 can be waivered when the pilot operates under a valid Remote Operator Certificate (ROC) and the specific flight mission has been approved by the Director of SACAA. Other requirements for the specific flight missions may include:

- Local road closures for public use when operating an RPA over or along a public road
- Written permission obtained from government authorities or structure/building owners
- Specifically requested conditions approved by the Director of SACAA.

2.5 Bridge inspection types and activities suited for RPA-based inspections

Gillins *et al.* (2018) investigated bridge inspection requirements that were suitable for RPA-assisted inspections in terms of the American Association of State Highway and Transport Officials (AASHTO) and the Federal Highway Administration (FHWA). They used a rating system to express the usefulness of an RPA in obtaining bridge report data for the inventory, condition ratings and appraisal elements. The rating system was also used for the different types of bridge inspections as required by the AASHTO. A scale of 1 to 4 was used, where 1 = not useful, 2 = limited use, 3 = useful and 4 = very useful. A summary of their findings is shown in Figure 2.3.

The subitems (see Figure 2.3) of the inventory data, conditional ratings and appraisal elements are largely embedded in the StrumanBMS Inventory Module and the Inspection Module, and therefore relevant to this study. Furthermore, the AASHTO bridge inspection types were also cross-referenced to the inspection types as required in South Africa. For example, the TMH19 equivalents to the AASHTO’s Initial and Routine Inspections are Completion and Principal Inspections, respectively. The South African equivalent inspection types and requirements are shown in brackets in Figure 2.3.

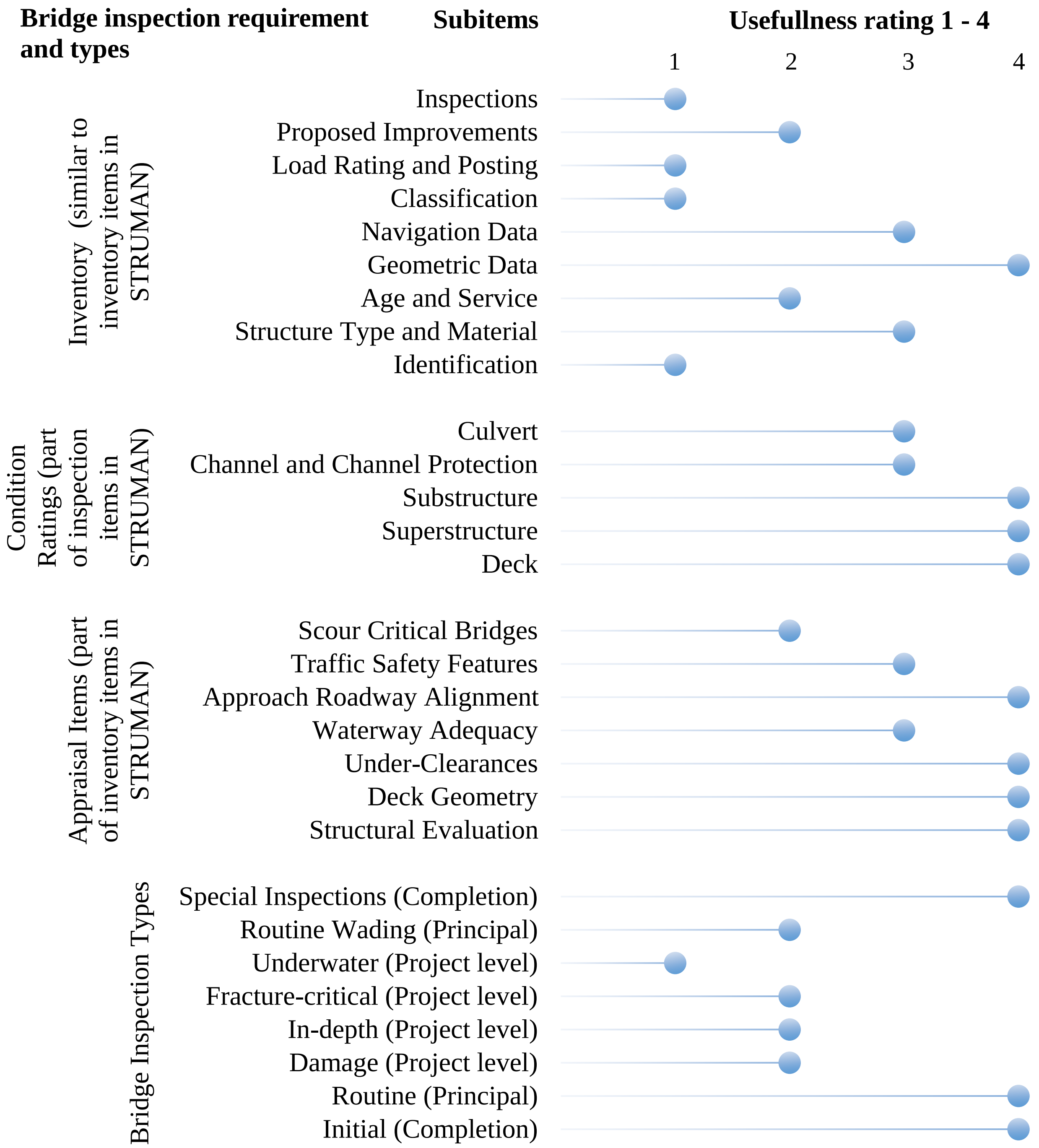


Figure 2.3 Usefulness of RPAs in terms of the inventory, conditional ratings, appraisal elements and types of bridge inspections in terms of FHWA and AASHTO requirements (adapted from Gillins *et al.*, 2018).

Several of the bridge inspection requirements and subitems (see Figure 2.3) where an RPA could facilitate the inspection process were rated as useful and very useful. Nordengen and Fleuriot (1998) found that specialised equipment was seldom needed for network level bridge inspections in South Africa and the use of high-quality binoculars and a camera with a zoom and flash function were adequate and suitable for most bridge inspection requirements. It is important to note that off-the-shelf commercially available RPAs were not available for evaluation purposes at the time of their research and that Part 101 only came into operation in 2015. The TMH19 does not refer to the use of an RPA for any inspection activities or as part of the equipment required for bridge inspections;

however, mention is made of using a boat, an Under-bridge Inspection Unit (UBIU) and binoculars where physical access is difficult and/or unsafe.

Nordengen and De Fleuriot's (1998) investigation showed the importance of inspecting and evaluating the approach roads, watercourses and roadways underneath the bridge when assessing a bridge and assigning ratings to its structural defects. They found that the lack of adequate photographs had resulted in additional costs for revisiting bridges to obtain the required information. It was therefore recommended that more than the minimum number of photographs should be taken for post-inspection discussion purposes in the office or off site with clients and co-workers. Although this information can be obtained through conventional methods, the study by Gillins *et al.* (2018) showed that RPAs were very useful and effective in facilitating this process.

RPAs are also effective for capturing detailed photographs of structural elements in difficult to reach access areas as opposed to human-based methods. This makes routine inspections more feasible due to the enhanced quality of photographs and enabling structure owners to actively monitor visual deterioration such as corrosion, progression of structural cracks, embankment erosion and safety issues (Darby, Hollerman & Miller, 2019).

Bridge inspectors can review numerous inspection items from high-quality inventory photographs and use them for planning and quantitative assessment purposes as well as for obtaining a holistic view of the structure and its surroundings. Important photographs that can be captured by an RPA during network level inspections and their corresponding TMH19 inventory views (shown in brackets) are listed below and graphically shown in Figure 2.1:

- The bridge in elevation from both sides showing the full height of the abutments, piers (if applicable) and the total deck length. (Views 1 & 2)
- Approach roads viewed along the road centreline leading to and away from the bridge as well as the roadway. This would enable the inspector to see whether the transition onto the bridge is smooth, whether the fill is stable, and whether there are other obvious defects that would affect the safety of road users to cross the bridge. (Views 3 & 4)
- The down and upstream sides of a river for a road-over-river bridge. This will enable the inspector to observe changes in the stability of the embankments and waterway as well as the water flow (free-flowing or blocked) on the bridge. (Views 5 & 6)
- Both sides of the superstructure (deck) edge. This would enable the inspector to see deflections in the deck profile and leaking joints. (Views 7 & 8)
- Typical view of the piers (for a multi-span bridge) and abutments. This could assist the inspector with high-level checks for structural integrity and changes. (Views 10 & 11)

After conducting a pilot concrete repair and rehabilitation project based on the 2003 BMS assessment data of WCG, Nell, Newmark and Nordengen (2008) noted the importance of key inventory photographs to be taken at regular intervals for flood behaviour analysis, river bed behaviour, accident cases, structural damage, waterway scour, debris build-up and a historic record of retrofitting and repairs to bridges and major culverts.

2.6 Chapter summary

Literature shows that conventional bridge inspection practices are time consuming, costly, unsafe and inefficient, and lack repeatability in terms of quantitative accuracy (Phillips & Narasimhan, 2019; Xu & Turkan, 2019; Perry *et al.*, 2020). Numerous studies have sought to address these issues through the utilisation of RPAs as either:

- A supplementary tool to conventional bridge inspection practices, with a specific focus on the detection of structural defects, or
- The incorporation of RPA technology into a fully or semi-automated and streamlined bridge inspection process.

Even though the South African requirements for bridge inspections on a network level are similar and in line with their international equivalents, there are differences in terms of inspection frequencies, types of inspections required, and the associated level of detail required for each inspection.

The CR2014 is not specific in terms of the method of safety assessment, data required or management of inspection data. The safety inspection process must be determined by the relevant structure owners and must be comprehensive enough for a competent person to render the structure safe for continued use.

The TMH19 is specific in terms of the inspection types, frequencies of inspections and all associated processes and methods of obtaining, managing and analysing inspection data. Principal inspections and completion inspections require inspectors and their technical assistants to obtain both inventory and inspection data. Although it is considered essential for road authorities, the acquisition of inventory photographs and data is a laborious and time consuming task for bridge inspection teams and at times may be dangerous.

Previous research on utilising RPAs for bridge inspection activities has shown limited or no proven improvements in terms of time, cost, safe practices, repeatability and accuracy over the conventional approaches. This led to further investigations into the benefits of using RPAs over or in addition to the conventional bridge inspection approaches in the Western Cape.

In response to the shortcomings and lack of information about innovative methods to acquire inventory photographs and data in an effective manner and ensure legal compliance, a unique bridge inventory data acquisition approach and virtual safety assessment were investigated for the DTPW. This approach encompasses the utilisation of RPA technology, visual-based systems and photogrammetry and is unique because it is expected to:

- Make use of RPA technology to meet the TMH19 inventory requirements
- Promote adherence to the provisions of the CR2014 safety inspections
- Be scalable for implementation on a network level.

3 Research methodology

3.1 Introduction and overview

This chapter provides an overview of the research methodology applied in this study. Qualitative and quantitative research approaches are discussed, and reasons are given why a combination of these approaches (i.e., a mixed-method approach) was selected to achieve the aim and objectives of the research. The chapter further describes the data sources, collection methods and a breakdown of the data analysis processes used for each data source. Chapter 3 concludes with a brief overview of the Stellenbosch University Ethics Approval Committee provisions and summary of the research methodology.

3.2 Research design

The research design provides a framework that was used throughout the study for identifying and describing:

- Types of data required
- Appropriate methods used for collecting and analysing data
- Synthesis of the data to achieve the aim of the study (Van Wyk, 2015).

According to Leedy and Ormrod (2015), this can be achieved through understanding what data are required, where the data are located, how the data will be obtained, the limits/criteria for acceptable data and the interpretation of the data.

The research design for this study followed a mixed-method approach where existing textual and numerical data were analysed, and primary data were generated through surveys, observations and RPA test flights at selected bridge sites. The data was obtained through both qualitative and quantitative research approaches.

3.2.1 Qualitative research

Qualitative research is a systematic and inductive approach of collecting, organising and interpreting textual information, such as interview guides and observation tools, to characterise the perspectives and experiences of participants, and to generate comprehensive and in-depth descriptions of processes (Mack, Woodsong, MacQueen, Guest & Namey, 2005).

In terms of this study, an interview guideline was developed that acted as a qualitative framework to facilitate conversations with the interviewees and to prevent the discussions from veering off in a direction not relevant to the research topic. The guideline consisted of a list of main questions as well as a brief overview of the study, reasons why the participants were chosen, procedures and confidentiality concerns to help the interviewees understand the intent of the study and the questions.

Inspectors and RPA pilots were observed while they were inspecting bridges and major culverts. The purpose of the observations was to make objective notes while the participants performed the bridge inspection activities. The observation notes were used for identifying individual perceptions, group connections, patterns of behaviour and salient factors as industry experts inspected the structures.

3.2.2 Quantitative research

Quantitative research seeks to explain and predict relationships between known variables in order to confirm and validate existing practices by using representative and large samples of data. A deductive and statistical analysis approach with objective criteria was used to analyse the data. The findings of the analysis are typically communicated in the form of numbers and used for describing correlations, variabilities, patterns and existing and future trends (Leedy & Ormrod, 2015).

In terms of this study, specific data obtained from the Western Cape Government's bridge management system were reduced to numerical datasets and summarised to determine bridge inspection quality control issues, cost of inspections, time used for inspections and current trends. Certain limits and criteria were adopted for data to be admissible in order to determine whether RPAs can be effectively used for bridge inspection activities on the Western Cape Provincial bridge stock.

3.3 Data sources and collection methods

Multiple data sources and collection methods were considered and used to give credence to the research findings.

3.3.1 Bridge Management System database of the Western Cape Government

The Western Cape Government's Bridge Management System database contains a collection of existing road infrastructure data. The bridge inventory and inspection data are managed through StrumanBMS software. This software uses Microsoft Access Database (MDB) files. Inspectors captured all the required inventory and inspection data of their assigned inspection package on StrumanBMS and exported the data as an MDB file. The MDB file was submitted online via OneDrive to the Western Cape Government. The system owner at the Western Cape Government collated the data and created a master MDB file containing the inventory and inspection data of the entire provincial road network. StrumanBMS allows users to convert and export selected data from the MDB files in both portable document format (pdf) or Microsoft Excel format for analysis purposes. The inventory data are also uploaded to the Departmental Oracle server and made available to the public on the Road Network Information System website.

3.3.2 Field observations during actual principal bridge inspections

Qualitative field observations rely on personal observations of people in their natural setting as the source of data. These observations are semi or unstructured to allow researchers to shift their focus when different or new findings present themselves. Qualitative field observations are therefore flexible in nature and allow the researcher to capture unforeseen data sources and methods of obtaining data (Leedy & Ormrod, 2015).

Field observations were conducted at several bridge sites where principal bridge inspections were taking place on the provincial road network of the Western Cape. The observations were recorded in detail by means of personal notes and photographs that captured first-hand how the inspectors and their assistants conducted principal inspections. The notes were compiled on semi-structured observation sheets (Appendix C). It was therefore possible, without having to participate in the assessment activities, to construct an integrated picture of how certain inspectors conducted bridge inspections.

3.3.3 Interviews

The purpose of conducting interviews was to obtain individual perspectives in terms of using RPA technology for bridge and major culvert inspections. Key individuals were identified that were considered industry experts; these experts had knowledge of the research topic and were willing to speak about it. The goal of the interviews was to obtain a broad range of perspectives from all the participants. The interview sample size was not decided in advance due to the complexity of the research topic and was determined when no new perspectives, experiences, concepts and ideas emerged from the interview data, i.e., the theoretical saturation point.

The questions were structured as open-ended and non-directional, making this method of obtaining data explorative in nature and allowing the interviewer and interviewees to develop new ideas and/or explain their existing ideas and experiences in detail. The framework required the interviewees to explain a wide range of factors based on their personal experience and knowledge of bridge inspections and the RPA industry. This required the principal investigator to listen carefully, make notes and explore specific comments or answer accordingly.

The interviews were conducted on a one-on-one basis via Microsoft Teams and at a time of the participant's choosing. Initially it was envisaged that participants would be interviewed on their own companies' premises. However, due to the COVID-19 restrictions it was decided that the interviews would be conducted via Microsoft Teams. The interviews followed the predetermined questions in the interview guideline. The interview questions were shared with the participants at least one week before the interview took place. The interviews were not voice recorded or filmed. The principal investigator made detailed written notes for each question during the interview. The notes were formalised after the interview and sent to the relevant participant via email for verification and validation purposes before using them in the study.

A total of 21 interviews (18 accredited inspectors and 3 RPA operators) were conducted and analysed for this study. The basic interview analytics are summarised in Table 3.1.

Table 3.1 Interview analytics.

Metrics	Analytics
Time spent per interview	Between 60 minutes and 80 minutes, including personally taking detailed notes of responses.
Time spent in post-processing of notes	Approximately 60 minutes which comprised collating, reviewing and refining the notes before they were sent to the relevant participant for validation purposes.
Interview validation process	Approximately 25 minutes. This entailed emailing the detailed notes of responses to the relevant participant and updating responses in line with feedback from the participant.
Total time spent on obtaining and validating interview data	Approximately 33 hours in total. The total duration excludes the compilation of the interview guideline and the process of identifying and inviting suitable and willing participants.

The interview administration and collection of interview data were managed on a Microsoft Excel spreadsheet.

3.3.4 RPA test flights

RPA test flights were conducted at two bridge sites in the Western Cape to research the feasibility, limitations and capabilities of RPAs for inspecting bridges. Different RPA platforms were used and tested in this study. The capabilities and effectiveness of the RPA platforms in terms of bridge inspection applications were in line with other platforms in similar studies (Hiasa, Karaaslan, Shattenkirk, Mildner & Catbas, 2018; Xu & Turkan, 2019). The RPA platforms were compared using several standards of measurement including price, camera, size, payload and flight time to provide an overview of the benefits and drawbacks of each platform. The RPA test flights were conducted to determine effectiveness in terms of cost, quality, time, ease of use, skills required, repeatability and processing requirements. Additional features and capabilities using this technology were also researched with the aim of enhancing future bridge inspections.

3.4 Data analyses

The data sources were analysed using both deductive and inductive reasoning processes. Statistical procedures were applied to analyse the quantitative research, while the analysis of the qualitative research was more subjective in terms of searching for patterns, conflicts and similarities in the data (Leedy & Ormrod, 2015).

3.4.1 Bridge Management System database of the Western Cape Government data analyses

Data analysis in terms of the BMS database refers to the process of reviewing, cleaning and transforming raw structural data for it to be useful and easy to interpret (Ceneda, Gschwandtner & Miksch, 2019).

The 2019 bridge inspection data were analysed through descriptive and inferential statistics to determine whether, where and how RPAs can be incorporated in future network level structure inspections. Descriptive statistics refer to statistical methods used to describe the bridge inspection data and inferential statistics consist of statistical methods to test the relationships between variables identified in the data sources (Kremelberg, 2014).

3.4.2 Field observations of bridge inspection data analyses

The purpose of the field observations was to identify and observe which aspects in conventional visual assessments and TMH19 methods were time consuming and/or affected the quality of data while actual bridge inspections were underway. Notes were taken in line with the approved observation sheets and analysed with reference to the following items:

- Inspector type
- Whether an RPA was used on site or not
- Description of the site
- Inventory data collection in the field
- Condition assessment of the structure
- Total duration of time spent on site
- Method/process of conducting the visual assessment
- Description of activities that seemed to be time consuming.

3.4.3 Post-interview data analysis

The purpose of interviewing the participants was to elicit descriptions of current bridge inspection practices in terms of TMH19 requirements that were considered time consuming, costly and/or hindering the quality of data. It was also important to obtain an understanding of the dynamics of engineering firms and the RPA industry in the Western Cape and how well new technologies or changes in current practices were received or initiated.

Bridge and culvert inspectors were interviewed first to gain knowledge of current inspection practices and whether they had made use of RPA technology for bridge inspections. Subsequently, RPA operators were invited to participate in the research study.

3.4.4 RPA test flights data analysis

The purpose of the test flights was to determine the capabilities and effectiveness of different RPA platforms for bridge inspection purposes on a network level. The data were analysed in terms of the flight logistics and technicalities of the RPA system around bridge structures. The RPA platforms were tested at two selected bridge sites for comparison and analysis purposes. The regulations and provisions of Part 101 (see Section 2.2) as well as CR2014 and TMH19 (see Section 2.3) were checked to ensure compliance.

3.5 Ethics and confidentiality

The activities related to obtaining information from the Western Cape Government's BMS database, conducting interviews and making observations complied with the Stellenbosch University Ethics Approval Committee provisions (REC-2019-11584). See Appendix L. All participants were informed prior to and after the observations and interviews that they were free to withdraw any of their responses or completely remove themselves from the research project at any time.

The participants' personal and company information was not recorded and did not form part of this research. The observation and interview sources of the data were cited as anonymous. The participants were not requested to provide any personal information which could identify them as an individual. The only form of personal data required was the participants' job title, age and area of expertise. The names of the participants and the names of their companies were not disclosed. All recorded correspondence between the participants and the principal investigator was confidential; only the principal investigator and his supervisor had access to this information.

The responses obtained during the interviews were assigned a unique reference number, which was used to identify data in the study itself. Furthermore, no names of participants were recorded or added to the observation sheets. All record keeping was by means of notetaking and photographs only; these were emailed to the respective participant for validation and approval before using it in the study.

3.6 Chapter summary

This chapter outlined and discussed the research methodology used to achieve the aim and objectives of the study. The data sources and collection methods included the BMS database of the WCG, field observations of bridge inspectors, interviews with accredited bridge inspectors and RPA operators, and test flights. The data collection methods comprised qualitative and quantitative approaches to obtain the relevant information applicable to this study.

Data from the BMS database are analysed and the results of the 2019 principal inspections for the Western Cape Government are given in Chapter 4. The findings of the bridge inspection survey comprising field observations and interviews, RPA platforms used, RPA test flights and results are collated and described in Chapters 5 to 8. Chapter 9 provides a synthesis of the data and information obtained by following the research methodology to determine the feasibility of utilising RPAs for bridge inspection activities on the provincial road network of the Western Cape. Chapter 10 offers recommendations to address shortcomings in regulatory provisions and in current technical manuals; specific recommendations for the DTPW; and recommendations for future studies.

4 Data analysis of the 2019 principal inspections for the Western Cape Government

The data analysis of the principal inspections that were performed in 2019 on the Western Cape provincial road network included the collation and analytics of the inventory and inspection data of 2738 road structures. The purpose of the analysis was to provide a factual representation of the inspection data and to detect gaps, trends, outliers and significant aspects which could be used as facilitators for future RPA-assisted bridge inspections.

This chapter presents a brief background of the scope of works for the WCG principal inspections and reflects the results of the abovementioned analytics in terms of key highlights, the quality of data received, the time spent during the inspections and the cost of the inspections.

4.1 Background and scope of works for the 2019 principal inspections

The Department of Transport and Public Works of the Western Cape Government made use of several consulting engineering firms to conduct principal structural inspections on the provincial road network in 2019. A total of 2738 structures were inspected: these included bridges (860) and major culverts (1769). The above total number of structures excluded sign gantries (30) and retaining walls (79), which fall outside the scope of this study.

A total of 47 inspectors (see Figure 4.1) and their technical assistants completed the inspection works in approximately seven weeks at a cost of approximately R12.5 million (excluding reimbursable expenses). The cost included the:

- Professional time for inspection work and time driving between structure sites
- Data capturing and reviewing
- Reporting.

All the structures had to be checked against the TMH19 definitions and reclassified if required. It was important that the correct inventory, inspection, and photographic input sheets were used to obtain accurate and representative data. The inspection sheets are based on the structure class which was to be verified for each structure by the inspector.

The inspectors used the supplied GPS coordinates, WCG road numbers and kilometre distances to locate the structures. However, the location data had to be verified in the field, as the existing data had last been updated in 2002/2003 and might have been inaccurate.

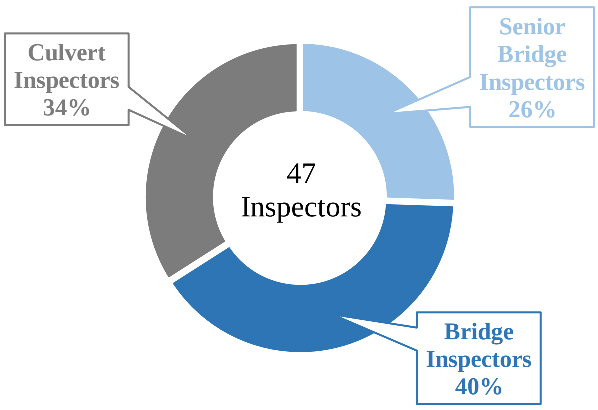


Figure 4.1 Distribution of inspector types.

Ultimately, the inspectors were required to capture all the inventory and inspection data on the StrumanBMS software. The data were sent to WCG for quality assurance, verification and approval.

The consulting firms also prepared reports containing their main findings based on their assigned inspection packages.

4.2 Key highlights of the inspection data

This section discusses the key highlights of the 2019 inspection data and demonstrates the complexity of the WCG bridge management system in terms of the provincial road network structure stock size, largest and smallest inspected structures, and age of the infrastructure.

4.2.1 Structure stock size

The provincial road network structure stock size refers to the total amount of captured structures (2629) on StrumanBMS. Each structure is assigned a class (bridge or major culvert) as per the TMH19 definitions and subclass (small, medium, large and very large for bridges only). This is important in terms of the inspection and inventory requirements for each structure class as well as for the remuneration of consulting engineering firms.

Figure 4.2 shows the total number of bridges and major culverts that were inspected in 2019 as well as the distribution of the structures in their respective subclasses. The definitions of the structure type, class and size category may be viewed in Addendum E. Of all the inspected structures (2629), the structure class and subclass distribution differed most, as shown below:

- Of all the inspected structures, 67.3% were major culverts and 32.7% were bridges
- In terms of the bridge subclasses for the entire structure stock: 10% were small, 14% were medium, 6% were large and 2% were very large
- In terms of major culvert subclasses for the entire structure stock: 26% were small, 20% were medium and 21% were large.

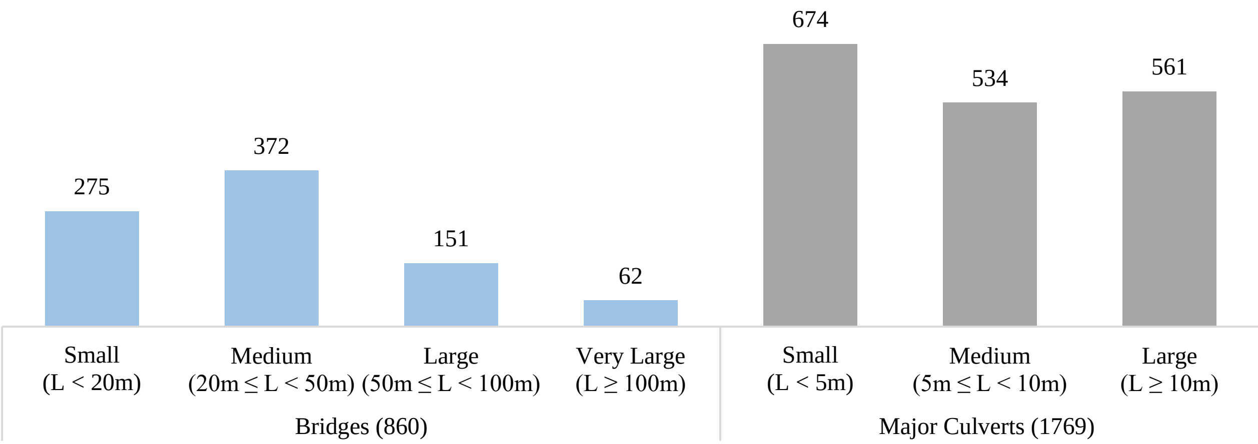


Figure 4.2 The distribution of bridges and major culverts on the provincial road network in terms of size category (‘L’ refers to the overall length of the structure).

4.2.2 Examples of typical large, inspected structures on the provincial road network

The largest structures in terms of the longest overall lengths, longest spans and highest supports on the provincial road network are shown in Table 4.1. These structures constitute 2% of the total bridge stock on the provincial road network.

Table 4.1 Examples of typical large structures in terms of overall length, longest span and highest supports.

Overall length	Longest span	Highest support	Bridge no. and location	Photograph of bridge elevation
687.1 m	68.6 m	13.17 m	B6001 at the Koeberg Interchange, Cape Town	
635 m	68.6 m	14.47 m	B6000 at the Koeberg Interchange, Cape Town	
528.9 m	12.9 m	5.5 m	B3403 crossing the Breede River at Nekkies, Worcester	
503 m	40 m	34 m	B4794 crossing the Sonderend River at Draaiberg, Theewaterskloof dam	

4.2.3 Examples of typical small structures inspected on the provincial road network

The smallest structures in terms of the shortest overall lengths, shortest spans and lowest supports on the provincial road network are shown in Table 4.2. These structures fall within the 26% subclass distribution of the major culverts (see Figure 4.2).

Table 4.2 Examples of typical small structures in terms of overall length, longest span and highest supports.

Overall length	Longest span	Highest support	Structure no. and location	Photograph of structure elevation
3.1 m	3 m	0.9 m	C11333 underneath the R61 near Beaufort West	
3.6 m	2.4 m	2.4 m	C10806 at Sekretarisbos kloof in Caledon, Napier	
7.3 m	3 m	1.19 m	C10950 at Bellair near Ladysmith	
9.38 m	4 m	1.5 m	C11901 underneath Church Street near Dysselsdorp	

4.2.4 Age of the provincial bridge stock

The typical service life of bridges under normal operating conditions are 50 to 100 years before major repairs, rehabilitation, retrofitting or complete replacement must be considered (Jensen, 2020; TMH7). Based on the information received during the 2019 bridge inspections, the construction dates of 1369 structures could not be obtained due to the lack of as-built drawings and recorded information. The remaining structures with as-built records were used to determine the age of the provincial bridge stock.

Approximately 49.5% of the bridges and major culverts are older than 50 years, and 26.6% of the structures are older than 60 years. These percentages only reflect the age of the bridge stock with known construction dates. The oldest recorded bridge (see Figure 4.3) on the BMS was built in 1825 and widened in 1935.

Figure 4.3 Oldest recorded bridge on the provincial road network of the Western Cape.

4.2.5 Salient aspects of data received after inspections

The salient aspects of data received refer to the total submission size of the StrumanBMS MDB file, the photographs and the report, as well as the types of cameras used for the inspection (see Table 4.3).

Table 4.3 Salient aspects of data received after inspections.

Salient aspects	Description	Total size or amount
Inspection deliverables	Total size (GB) of MDB files, photographs and reports	44.6 GB
Photographs only	Total number of photographs uploaded	56636
	Total size (GB) of all photographs	40.77 GB
	Average photograph size (MB)	0.72 MB

The minimum technical specifications for digital cameras in terms of the WCG scope of works document were as follows:

- Type: Digital camera
- Location data: GPS enabled for photograph geotagging (Geodetic system: WGS 84)
- Effective pixels: 5 Mega Pixel minimum capability
- Lens: 10 x optical zoom function
- Vibration reduction: Lens shift and electronic vibration reduction
- File format: Joint Photographic Experts Group (JPEG)
- Flash: Yes.

Several of the cameras used during the inspections did not meet the minimum requirements as per the WCG scope of works. Some inspectors even made use of integrated cell phone and tablet cameras. Table 4.4 shows all the cameras used during the inspection. The cameras that did not meet the minimum requirements are written in italics.

Table 4.4 Digital cameras used during the 2019 principal bridge inspections. The cameras written in italics did not meet the minimum specifications.

Digital cameras used	Optical zoom
Nikon Coolpix AW130	*5*
Nikon Coolpix AW100	5
Nikon Coolpix P610	60
Nikon Coolpix S9500	22
Nikon Coolpix S9900	30
Nikon Coolpix S9300	18
Nikon Coolpix W300	5
Nikon Coolpix P900	83
Canon PowerShot D30	5
Canon PowerShot Sx280 HS	20
Canon PowerShot Sx230 HS	14
Canon PowerShot Sx260 HS	20
Sony DSC-HX400V	50
Sony DSC-HX9V	16
Fujifilm FinePix XP140	5
Panasonic DMC-Ft5	4.6
Xiaomi Redmi Note 7	0
Huawei POT-LX1AF	0
Apple iPhone XR	0

4.3 Quality control of inventory and inspection data received

Quality control is an essential part of visual inspection to reduce the probability and consequences of failing infrastructure. A critical review was undertaken to determine the quality of the inventory and inspection data received from the consulting engineering firms. The quality of data was evaluated against several important requirements and deliverables as outlined in the TMH19. The purpose of the review was to check the data for completeness and obvious errors. The results of the critical review highlighted numerous quality issues and common problems, as outlined and explained below.

4.3.1 Inventory and inspection photographs

The inventory and inspection photographs are a very important aspect of bridge inspections in terms of creating a visual record of the structures. The photographs are used as reference material for post-processing of inspection ratings and motivation purposes for immediate make-safe and future rehabilitation or structure replacement projects. Therefore, high quality photographs are essential for any bridge management system.

In terms of all the inspected bridges and major culverts, an extensive range of photographic issues were identified, as detailed below:

1. 5% of all the inspected structures had major photographic data issues. Major photographic data issues refer to photographs not being linked to the StrumanBMS software, photographs not uploaded, incorrect structure inspected, incorrect photographs, missing photographs, and deleted metadata such as the date, time, camera details and geotagging.
2. 15% of all the inspected structures did not have descriptions assigned to the inspection photographs. All inspection photographs must have descriptions. The description typically includes the nature and the extent/size of the defect, e.g., Span 3 Deck Midspan – 2 mm wide transverse bending crack.
3. 13% of all the inspected structures did not have orientation sketches uploaded to the database. A photograph must be taken of the structure orientation hand sketch which indicates the orientation and the numbering of the sub-items of the structure.
4. 8% of all the submitted photographs exceeded the allowable average photograph size limit of 1 MB given in the scope of works. The submitted data were however checked against 1.5 MB average size limit during the QC process. Photographs exceeding this limit were flagged as too big and had to be resized.
5. 26% of all the inspected structures had missing location metadata assigned to the photographs. The scope of works required that all the photographs be geotagged. If 25% or more of photographs per structure were not geotagged, the submission was flagged. Inspectors could use software to geotag selected photographs where GPS signal was poor, such as inside a culvert or underneath a bridge.

Spot checks were also conducted on the image quality of the inventory and inspection photographs. Inventory photographs had to correspond with the inventory photograph description (Appendix D). Inspection photographs had to clearly show the degree and extent of the defects and have a written description of the defect assigned to the photograph to understand the relevance rating. Table 4.5 shows typical examples of poor- and good-quality inventory photographs of the same views taken during the 2003 and 2019 bridge inspections.

Table 4.5 Examples of poor- and good-quality inventory photographs.

Year, bridge number and photograph description	Photograph taken during actual bridge inspections	Image quality (good/poor)
2003, B9038 – Structure outlet in elevation		Good
2019, B9038 – Structure outlet in elevation		Poor - image is distorted (fisheye view)
2003, B4135 – Structure inlet in elevation		Poor - full extent not shown; distracting elements
2019, B4135 – Structure inlet in elevation		Good

4.3.2 Access to the structures

Inspection teams were required to give a brief description of their access to the required structure to perform the inspection and to obtain inventory data. Of the 2629 inspected structures, 388 structures had access issues. As a result, 95 structures were not inspected at all and 127 structures were partially inspected; despite the access issues, the remaining 166 structures were fully inspected. Typical access issues that were experienced by the inspection team along with an explanatory inspection photograph are shown in Table 4.6.

Table 4.6 Examples of access issues on the provincial road network.

Structure number, location and access description	**Photographs taken by inspectors during the actual 2019 bridge inspections**
B4831 crossing Grootvadersbos River near Swellendam. Easy access. Binoculars were adequate to inspect elements spanning the river.	
B2219 crossing the Great Brak River, Mossel Bay. Easy access. A boat was however required for deck and bearings.	
C11241 underneath Kammanassie road near George. Difficult access. Bush clearing and fence climbing required.	

B3089 crossing the Goukou River near Hessequa. Easy access. A boat (kayak) was however required.	
C10329 in the Hex River, Breede Valley. Difficult access. The inlet and outlet were completely blocked with vegetation.	
B9009 crossing the Voëlvlei irrigation canal near Hermon. Difficult access. The steep embankments and deep concrete-lined canal impeded access.	

4.4 Time spent during inspections

The time spent at each structure (categorised in terms of structure class and size category) were recorded by the inspectors as it was required for remuneration purposes. Time-related items included:

- Fieldwork and driving between structures
- Data capturing and reviewing
- Reporting.

The average time that was spent on inspection work as outlined above for each structure class and size category were calculated and summarised (see Figure 4.4).

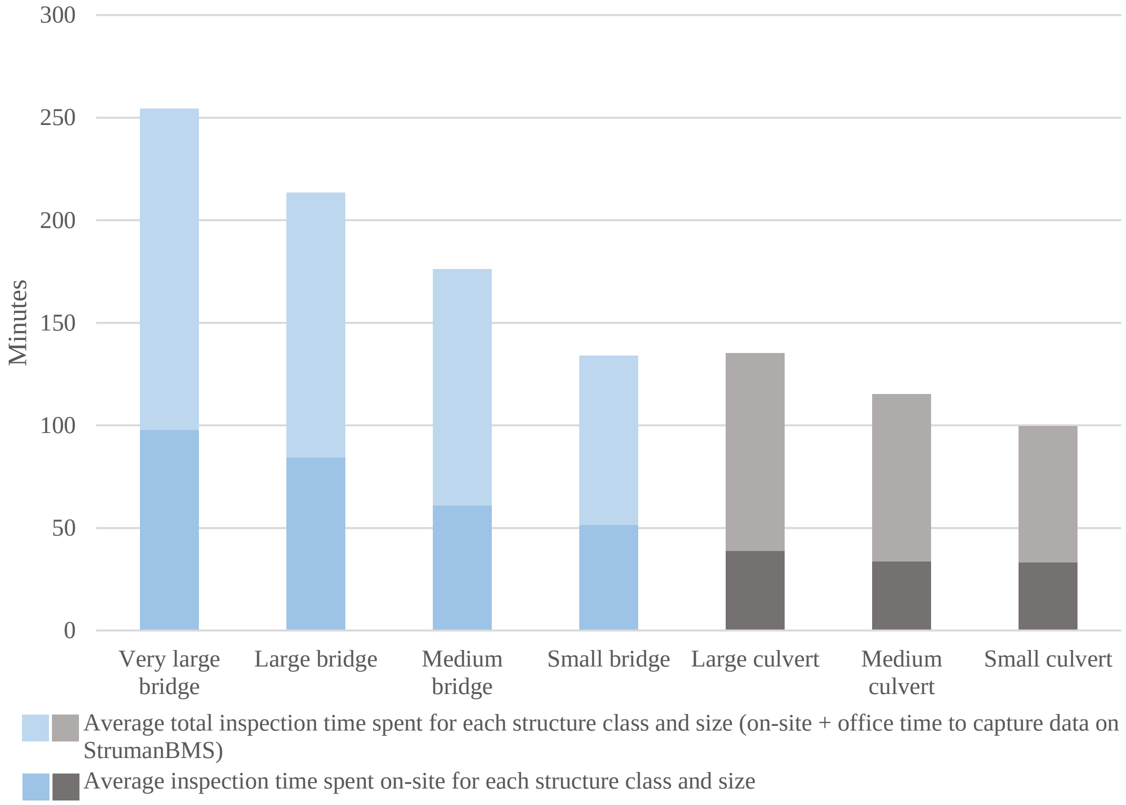


Figure 4.4 Average time spent on bridge inspection activities for each structure type and subclass.

Figure 4.4 shows the structure class and size categories ranging from the largest structure types (very large bridge) on the left to the smallest structure types (small culvert) on the right. As expected, the time used for the inspection work decreased for smaller structures and increased for larger structures. The total average inspection time spent on small bridges and large culverts was approximately the same while the average on-site time for large culverts was less than that for small bridges. This is because large major culverts include causeways and drifts which can easily exceed the linear length limit of small bridges (length less than 10m). Major culverts have fewer inspection items to complete and are typically less complicated, depending on the defects identified.

As illustrated in Figure 4.4, the on-site inspection time for all the bridges was approximately 38% of the total average inspection time for bridges. The on-site inspection time for all the major culverts was approximately 30% of the total average inspection time for major culverts.

The on-site inspection time percentage for each structure class and size category when measured against the total average inspection time is shown in Table 4.7.

Table 4.7 Percentage of the total inspection time spent on site and post-processing for each structure class and size category.

Structure class and size category	Percentage of the total inspection time used on site	Percentage of the total inspection time used for post-processing
Very large bridge	38% of the total inspection time was spent on site.	62% of the total inspection time was spent on data capturing, reviewing and reporting.
Large bridge	40% of the total inspection time was spent on site.	60% of the total inspection time was spent on data capturing, reviewing and reporting.
Medium bridge	35% of the total inspection time was spent on site.	65% of the total inspection time was spent on data capturing, reviewing and reporting.
Small bridge	39% of the total inspection time was spent on site.	61% of the total inspection time was spent on data capturing, reviewing and reporting.
Large major culvert	29% of the total inspection time was spent on site.	71% of the total inspection time was spent on data capturing, reviewing and reporting.
Medium major culvert	29% of the total inspection time was spent on site.	71% of the total inspection time was spent on data capturing, reviewing and reporting.
Small major culvert	33% of the total inspection time was spent on site.	67% of the total inspection time was spent on data capturing, reviewing and reporting.

The above findings were corroborated during interviews with accredited bridge and culvert inspectors (see Section 5.2.2). Several inspectors deemed the post-processing (i.e., office work) of the inventory and inspection data obtained on site to be disproportionate to the actual fieldwork.

4.5 Cost of inspections

The hourly remuneration fee of inspectors and technical assistants was based on their total annual cost of employment at their respective firms. The actual claimable rates were calculated according to the Engineering Council of South Africa's Guideline for Services and Processes for Estimating Fees for Persons Registered in terms of the Engineering Profession Act No.46 of 2000 (Republic of South Africa, 2000). The total cost of the 2019 WCG inspections was calculated based on the actual claimable rates and the allowable time spent on the inspection activities. Figure 4.5 shows the average inspection cost per structure class and size. Figure 4.6 shows the total cost per structure class and size of all the inspected bridges and major culverts on the provincial network.

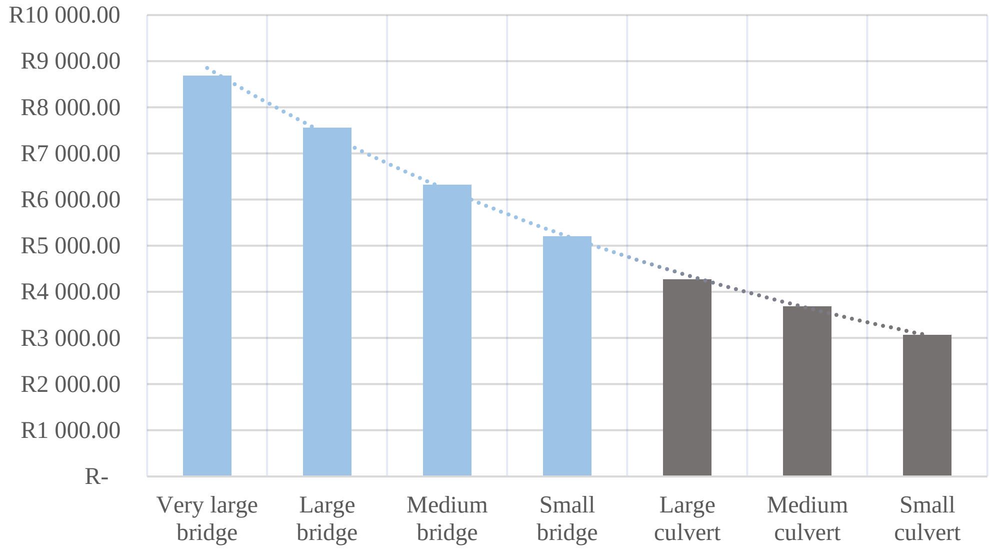


Figure 4.5 Average cost of inspection per structure class and size.

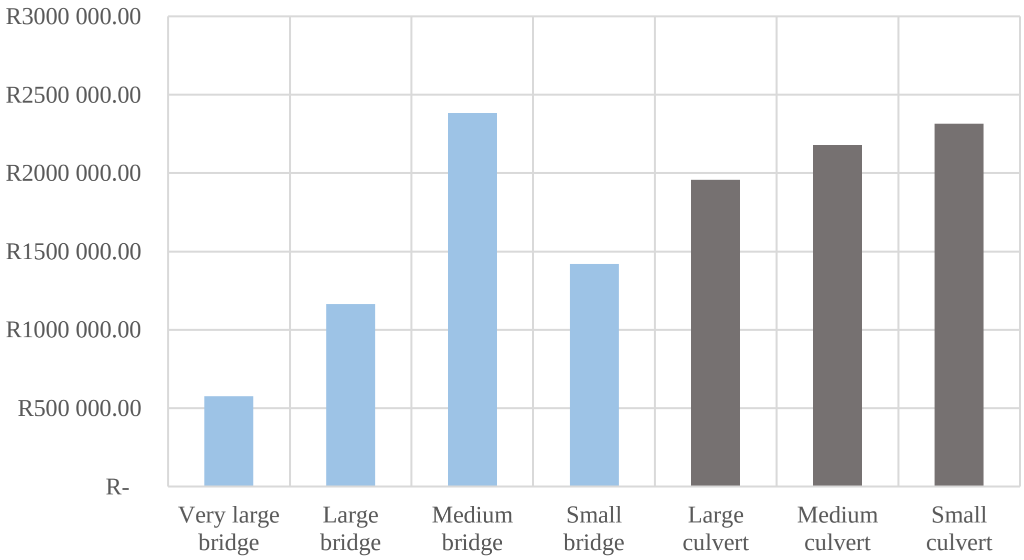


Figure 4.6 Total inspection cost per structure class and size.

Although very large bridges were the most expensive to inspect, they accounted for the least cost on the Western Cape provincial road network due to the small quantity of such structures.

5 Observations made during principal inspections and interviews with South African accredited inspectors and RPA operators

The use of RPAs for systematic and streamlined bridge inspection purposes to improve their cost-effectiveness and efficiency as well as the safety of inspectors is widely researched, specifically in the USA (Perry, 2019; Tomiczek *et al.*, 2019; Xu & Turkan, 2019). Limited research is however available on RPA-assisted bridge inspections based on the South African requirements and the local industry. Therefore, principal bridge inspection observations and interviews were performed to determine the degree and extent to which RPAs were used for bridge inspection activities in South Africa. No observations were made during the inspection of major culverts.

The survey consisted of personal observations made during principal bridge inspections which were performed by accredited bridge inspectors in the Western Cape, interviews with accredited bridge inspectors from several reputable consulting engineering firms in South Africa and interviews with RPA operators. This chapter presents the findings and results of the survey.

5.1 Observations made during principal bridge inspections in the Western Cape

Accredited bridge and culvert inspectors were observed during the 2019 WCG provincial principal bridge inspections. The purpose of the observations was to view and document current bridge inspection practices during actual principal inspections. The objectives of the observations were to:

- Attain a general feel for the bridge sites and surroundings in terms of access and safety
- Document different bridge inspection methods used by bridge inspection teams
- Record the durations of bridge inspection activities.

A total of five bridge sites were visited during the 2019 official principal bridge inspections for observation purposes.

5.1.1 Bridge sites and surroundings in the Western Cape

The five bridge sites that were selected for observational purposes during inspections are in different regional district municipalities (see Figure 5.1) to take the diverse topography of the Western Cape into account.

Figure 5.1 District Municipalities in the Western Cape Province (Corporate communication, 2021).

Access to the structure sites were generally perceived as easy, despite:

- Inspectors and technical assistants having to climb over barbed wire fencing, specifically at major culverts in rural areas
- Slightly overgrown vegetation in waterways and at the inlets/outlets of structures
- Steep embankments.

The following safety concerns were observed:

- Several snakes and wasps were encountered in and around the bridges and culverts during the hot weather in November and December.
- High traffic volumes and high-speed traffic along freeways and dual carriageways were considered unsafe and extended the field work times. Inspectors had to make certain adjustments to obtain the required inventory photographs at these sites.
- Certain days were very hot (approximately 35 to 40 degrees Celsius) and dehydration may have been experienced if the inspection teams had not made provision for staying hydrated.
- Polluted and contaminated rivers were encountered, posing health risks to inspection teams. The contaminated water bodies were often not accessed by inspectors, resulting in areas of a structure not being inspected.
- Safety concerns for inspectors in high crime/violence areas were noted, specifically along the N2 in the Cape Town area and the R43 near Worcester. Several homeless people were observed either living under or near structures, which also posed a safety risk to the inspectors during the fieldwork operations, particularly given the perceived high value equipment that inspectors are mandated to use.

5.1.2 Different bridge inspection methods used by bridge inspection teams

There were three primary methods (see Appendix C2) used by the inspection teams to obtain the inventory data and complete the visual condition assessments of the bridges and culverts. The main differences between these methods were in terms of:

- Pre-populating inventory and inspection sheets: Some inspection teams did not do any preparation work or desktop studies prior to the site inspection.

- Capturing photographs: Some accredited inspectors captured all the inventory and condition assessment photographs with one camera only on site. Some technical assistants captured all the photographs with one camera only on site. These photographs were collated and sorted at the office. Some inspection teams had two cameras where the technical assistant captured all the inventory photographs, and the accredited inspector captured all the condition assessment photographs.
- Populating inventory data: The technical assistant took all the measurements with the measuring wheel/tape/laser and populated the pre-printed inventory sheets on site.
- Populating condition assessment data: The accredited inspectors completed all the condition assessment inspection sheets.

It was observed that most mandated inspection equipment was used by the inspection teams; however, some of the inspection teams did not use binoculars, flashlights, the correct prescribed digital cameras, and ladders to access out-of-reach or out-of-site areas such as the bridge bearings or shaded areas of a bridge soffit. None of the inspection teams made use of an RPA.

5.1.3 Duration of bridge inspection activities

The time it took to collect the inventory data and the condition data, and the overall time spent on site were recorded during each site visit. The total time spent on site was measured between the time the inspection team arrived and the time they departed at each bridge site and is shown in Table 5.1.

Table 5.1 Time spent on site for bridge inspection activities.

Structure number and description	Access	Inspector type; sex	Time spent collecting inventory data	Time spent collecting condition data	*Total time spent on site
B4411; Medium bridge	Easy	Bridge inspector; male	58 minutes	83 minutes	123 minutes
B4413; Large bridge	Easy	Bridge inspector; male	35 minutes	65 minutes	75 minutes
B4417; Large bridge	Easy	Bridge inspector; male	24 minutes	36 minutes	43 minutes
C11208; Small culvert	Easy	Culvert inspector; male	19 minutes	15 minutes	22 minutes
C10641; Medium culvert	Slight obstructions	Culvert inspector; male	51 minutes	45 minutes	53 minutes

*The total time spent on site at each structure was not the sum of the inventory and condition data collection times, as these activities occurred simultaneously. The total time spent on site was measured between the time the inspection team arrived and the time they departed at each bridge site.

The following observations were made regarding aspects that affected the time spent on site:

- Similar structures on the same route that were inspected by the same inspection team went quicker because of similar defects and inventory data which reduced time spent on site.
- Walking to and finding the correct position to capture the extreme photographs, i.e., elevations of large structures, was time consuming.
- Crossing very busy roads was time consuming and dangerous.
- Sometimes the digital cameras' built-in GPS (used for geotagging) did not connect, which delayed the inspection process.

5.2 Interviews with South African accredited bridge/culvert inspectors and RPA operators

Accredited bridge/culvert inspectors and RPA operators were interviewed to obtain and document their perspectives and opinions about current bridge inspection practices as well as the use of commercially available RPAs for bridge inspection purposes.

The objectives of the interviews were to:

- Find aspects in conventional visual assessments and the TMH19 methods that were time consuming and/or costly and/or hindered the quality of data
- Evaluate how RPAs could be used to address these aspects and to improve the effectiveness of visual assessments, if at all
- Determine the current and future bridge/culvert inspection trends in terms of using RPAs
- Synthesise the collected knowledge to develop an approach to incorporating RPA technology in future bridge inspections for the Western Cape Government.

A total of 21 accredited inspectors were invited to participate in the research. Three of the invited accredited inspectors did not respond to the invitation. After the aim and objectives of the study had been explained, personal, semi-structured interviews were conducted with 18 inspectors in accordance with the interview protocol (Appendix B). The basic demographics of the inspectors are shown in Figure 5.2.

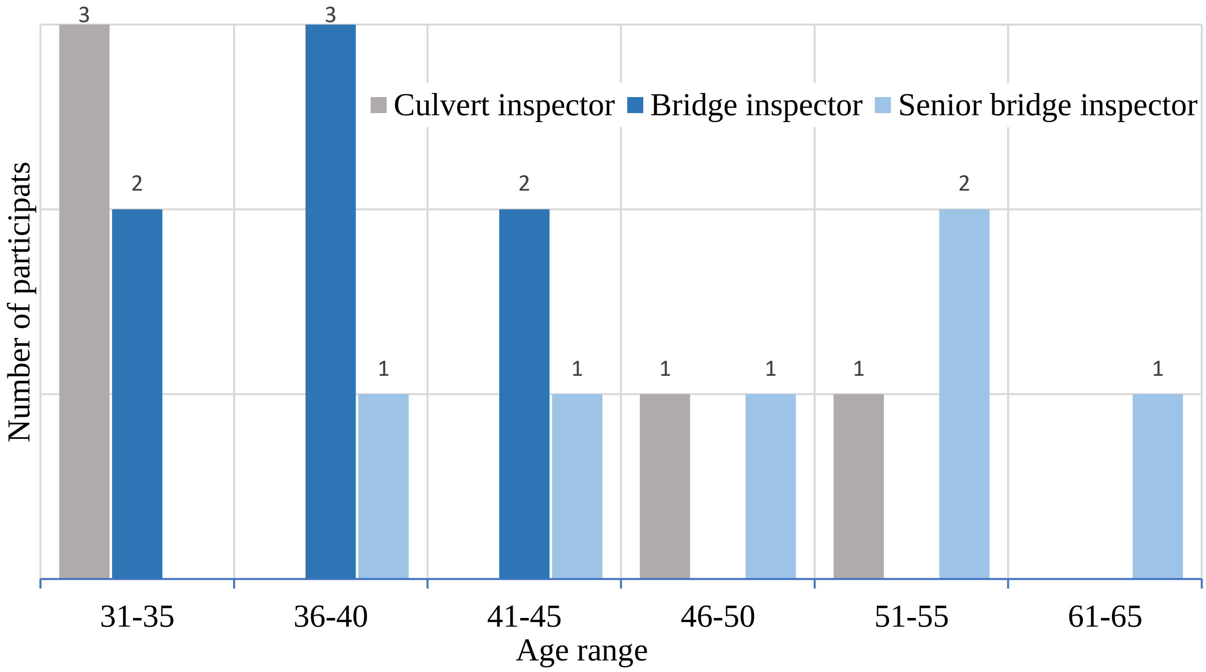


Figure 5.2 Age range distribution of inspectors.

Figure 5.2 shows a representative distribution in terms of age and qualifications of inspectors that provided inspection services to the Western Cape Government. The TMH19 accreditation requirements of bridge and culvert inspectors (Appendix K) that participated in the interviews are shown in Table 5.2.

Table 5.2 Qualifications and experience of inspectors (adapted from the TMH19 accreditation requirements for bridge and culvert inspectors).

Metrics	Culvert inspector	Bridge inspector	Senior bridge inspector
Qualifications	Qualified Engineer, Technologist or Technician	Professional Engineer or Professional Technologist	
Personal years of experience in bridge and culvert design	Five years obtained during the last 20 years	Five years (Engineer) or 10 years (Technologist) obtained during the last 20 years	10 years (Engineer) or 20 years (Technologist) over their careers with proven experience in Continuous Prestressed Bridges and a senior position involving the overseeing and advising of other bridge designers
Additional requirements	Attendance of a two-day COTO Structures Subcommittee accredited bridge and inspectors' course and passing the associated examination		

The commercial RPA industry in South Africa is currently very small, with a total of only 86 Remote Operator Certificates (ROCs) issued by the South African Civil Aviation authority to date (RPAS Operators, 2021). From these ROC holders, Zutari (previously known as Aurecon South Africa) and SNA Civil and Structural Engineers (Pty) Ltd are the only civil/structural engineering consulting firms with an ROC, restricted to corporate operations only. As the South African RPA industry is still in its infancy, no minimum qualifications or experience requirements were set for RPA operators to participate in the research.

Only six RPA operators were invited to participate in the study due to limited interest and/or their willingness to participate. Three RPA operators did not respond to the invitation. Two of the three RPA operators that participated in the interviews did not specifically answer the interview questions and rather spoke about the RPA industry and potential services they could offer/provide to the Western Cape Government. However, the responses were still considered insightful and relevant to this study.

After all the interview responses had been documented and validated, the information was populated into summary tables per question to obtain a holistic overview of each point or issue (Appendix B). The following paragraphs provide a synthesis of the interviews' main findings.

5.2.1 Time consuming aspects of conventional bridge/culvert inspections

The following aspects (in specific order) were identified by the interviewees as time-consuming tasks and are discussed in more detail:

1. **Capturing of inventory photographs and measurements.** Most of the interviewees considered the capturing of inventory data (photographs and measurements) as the most time-consuming process of bridge inspections. The inventory requirements for network level inspections were described as disproportionate to the requirements of the condition assessments. Some interviewees considered several of the inventory requirements as non-beneficial information and a waste of time to capture. For example, the capturing of the four extreme photographs (i.e., two elevations and two approach roads taken from opposite sides) of large bridges was very time consuming. One interviewee indicated that these photographs could take up to 30 minutes to capture for large bridges. Depending on the technical assistant's ability, this could take even longer.
2. **Transferring handwritten field inspection notes to the bridge management system software.** It was noted that in some cases the inventory data and the condition assessments were performed simultaneously by the bridge inspector and his/her technical assistant, resulting in some time saved. This was however not the preferred methodology of other bridge inspection teams. Several of the accredited bridge inspectors preferred to capture all the photographs themselves (see Section 4.1.1), leading to more time spent at each bridge site. Although it was considered time consuming, the capturing of inventory data added value to the bridge inspection process by forcing the bridge inspection teams to look into and around the structures from several positions and to orientate themselves with the structure and its surroundings. This was confirmed by younger participants who deemed it very important to get the structure orientation correct and familiarise themselves with the terrain and the structure on site.
3. **Uploading and renaming inventory photographs.** The uploading and renaming of inventory photographs and transfer of handwritten field inspection sheets to the bridge management system software were considered a comprehensive and time consuming task. Currently, the WCG uses StrumanBMS. One of the challenges with StrumanBMS is the paper-based process required to capture inventory and condition data on site using standardised pick lists. The capturing of information on paper and then having to convert the information to digital is very time consuming and prone to human error. In many cases it was

found that the capturing of data from paper to digital took the same amount of time as the actual on-site inspections. The complete data capturing and uploading process was also considered as disproportionate to the rest of the inspection process. Additionally, software hold-ups, errors and bugs resulted in more wasted time.

4. **Physical access to the structures.** In many cases access to structures, especially large river bridges and structures under flood, were considered time consuming. However, several interviewees mentioned that access to culverts were sometimes more difficult and time consuming than to bridges due to high embankments, heavy bush and vegetation, dense reeds and rivers restricting access. Access in some areas was very easy, as in the Karoo, compared to inspections in areas such as Mpumalanga where there are deep valleys and dense vegetation. The rivers in the Western Cape are full of reeds and anywhere near the coast there are many bushes, generally impeding access. Where access was problematic, it took additional time to complete the inspection. Other aspects escalating inspection times included tall piers on large structures making it difficult to see and inspect bridge bearings; highway bridges spanning several lanes with high traffic volumes; wide rivers; finding safe areas to park the vehicle which resulted in extended walking distances to the structure.
5. **Use of an Under-Bridge Inspection Unit (UBIU).** One interviewee mentioned that the most difficult and time-consuming process during bridge inspections was using an Under-Bridge Inspection Unit (UBIU) due to restricted access (not used during 2019 WCG inspections). There are only two UBIUs (see Figure 5.3) in South Africa; both are owned by SANRAL, and inspection teams must wait very long for the vehicle to arrive on site and move between sites as it travels at a snail's pace. Other interviewees mentioned that the UBIU could not be booked for a specific date and time and inspection teams had to wait for the UBIU to be available, making the use of it very inefficient. When used for inspection purposes, the vehicle moves at a crawling speed. The reach of the available UBIU mechanical arm is very short. Should the bridge have a sidewalk, the reach is even shorter. The biggest danger with using the UBIU was the possibility of the unit being hit by a car or truck whilst in use by the inspectors. As a result, certain firms required special permission and safety clearances before their inspectors could make use of the UBIU. Despite the negative aspects of using the UBIU, it remains an important tool for inspections as it places the inspector at arm's length of the structural elements, and it can also be used for bridge rehabilitation purposes.
6. **Travelling to bridge sites and between structures.** Driving to bridge sites and travelling between structures, especially in remote areas, were considered time consuming by several interviewees. This was however contradicted by one interviewee who mentioned that travelling between structures was not time consuming on Western Cape Government inspection packages because the structures were grouped together. It was found that insufficient or inaccurate spatial data for structures slowed down the entire bridge inspection process. For example, trying to find structures when they were not geotagged was very time consuming. Poor road kilometre and distance markers were additional challenges to overcome.
7. **Training and calibration of inspection teams.** Training of new staff was a time consuming and expensive process. Experienced team members spend considerable time to train new staff and to provide wide-ranging exposure to diverse technical problems on different types of bridges. The calibration of inspection teams is therefore very important, even between teams in the same firm. When inspection teams in the same firm were compared, it was observed that some team members were much more productive and efficient than other members doing

similar work. Some of the work included preparing for inspections (obtaining record drawings, printing field inspection sheets, planning travel logistics to and between bridge sites, etc.) and on-site inventory measurements.

5.2.2 Costly aspects of conventional bridge/culvert inspections

The cost of bridge/culvert inspections was directly related to the time it took to complete the inspections and submit the data to the client, i.e., the longer the time spent on site the higher the costs to the consulting firms and the client. For complex, large bridges with restricted areas requiring the UBIU, the costs would be even higher. Therefore, all the aspects that were considered time consuming were also considered costly. Refer to Section 4.5 for the WCG payment method.

Figure 5.3 SANRAL Under Bridge Inspection Unit (http://www.mowana-engineers.co.za/ files/22_xAXl.jpg) .

5.2.3 Aspects that hindered the quality of data in conventional bridge inspections

The following aspects were identified by the interviewees as aspects that compromised the quality of data and are discussed in more detail:

- Restricted access and site inspection equipment as required by the TMH19
- Human error
- Security risks
- Poor quality or limited information provided by the clients.

The quality of bridge inspection data was hindered during inspections of tall and large structures, specifically when a UBIU was required. It was found that even when using ladders, it remained problematic to inspect and capture photographs of bearings and the deck soffits. The camera zoom function and binoculars were difficult to use to identify defects and not always sufficient to inspect and determine the extent and degree of the structural problems. When water was present at structures, wading suits were required. Special care had to be taken not to puncture the wading suits when climbing over barbed wire fencing. A strong headlight was always required for long culvert inspections. It was noted that conventional access equipment is bulky, large and difficult to carry and take along to all the structures, especially for larger structures. One interviewee was however of the opinion that most of the structural elements were generally easy to view, except for bridge bearings.

It appeared that the quality of photos was related to finding a suitable position to stand and to take the actual photographs. The inside of the culverts was generally easy to inspect and take inventory measurements, except when dirty or full of water. In very dense vegetation/overgrown areas it is difficult to find suitable places to stand to take good quality inventory photographs.

Interviewees mentioned that it was not always possible to inspect everything that was required as per the TMH19. At certain bridge sites the bridge elements were too high and/or waterways were severely blocked, which restricted access. This hindered the proper assessment of the superstructure or getting access to piers founded in waterways. It further resulted in inspectors having to make assumptions or exclude the required information, which hindered the quality of the data.

Human error affecting data quality was found to be a major concern due to the laborious task of transferring data from paper to digital on StrumanBMS.

On-site security risks were a concern when suspect and suspicious people were encountered in the vicinity of the structure. Numerous inspection teams had to wait for or even come back another day before the environment was deemed safe for inspections to commence.

Several participants were of the opinion that the lack of record drawings (as-builts) or poor-quality record drawings made it difficult for inspection teams to corroborate their findings on site, resulting in increased time spent assessing structures.

5.2.4 Inspectors' knowledge of technology to improve bridge inspection efficiency

The technology available that inspectors were using or proposing to use to improve the efficiency for future bridge inspections is presented next. The question was open-ended to obtain as much information as possible from experienced inspectors about technologies used during conventional bridge inspections. The purpose was to determine whether any of the mentioned technologies could be incorporated into and/or integrated with RPA-assisted bridge inspections.

1. **High resolution cameras with GPS-enabled functions (stand-alone or cameras integrated with high-end smartphones).** Even with improved camera technology, the time of day when photographs were taken affected the quality of the photographs. For example, shadows and over/under exposure will result in poor quality photographs. It was found that having two cameras on site (one for the inspector and one for the technical assistant) was more effective and efficient in completing the inspections. The client's photograph specifications should be clear and detailed to ensure good quality photographs and using the correct cameras.
2. **Specialist cameras and digital scanners.** Thermographic cameras can be used to identify bridge delamination. Digital scanners such as lidar scanners have become more cost-effective and are very accessible; however, this technology will likely only be required when an actual rehabilitation is planned and not on a network level. Scanned data can be used for current and

future integration with Building Information Models (BIM) and Geographic Information Systems (GIS), especially for tracking changes.

3. **RPA technology.** Several participants mentioned the possible use of RPA technology but had limited or no personal experience using RPAs for bridge inspections. RPA technology is discussed in more detail in Chapter 4.2.6.
4. **Mobile devices such as tablets and laptops.** Some participants mentioned that the use of mobile tablets with specific software applications to capture data on site was effective, i.e., mobile data capturing. Weather-resistant tablets are currently available but have limitations such as handling and processing of photographs. When conducting field inspections, the inventory and inspection data must typically be captured on one tablet, which slows down the inspection process and does not work well. Numerous participants had no success in using a tablet or laptop in the field whilst doing inspections. Although there was consensus about the efficiency of capturing data live on site, several issues, problems and difficulties were experienced whilst making use of this technology on site.
5. **Structural health monitoring systems.** Several participants indicated that structural health monitoring systems were an available technology that could be used for remote monitoring. Digital crack gauges, displacement monitoring and dynamic analysis instruments were examples of these systems. None of these systems were used on a network level to inspect or determine the health of the Western Cape Government's bridge stock.
6. **Other technologies.** These include the use of ladders, mirrors mounted on poles, UBIUs, updated client databases for remote mobile access and optimised BMS interface and usability.

Several participants did not know of any technology currently available that would result in any time and cost savings for bridge inspections.

5.2.5 Current use of RPA technology for bridge inspections

The participants who had made use of RPAs for inspection purposes were asked to share their personal experience. The other participants were asked to explain why they had not considered using RPAs. Only three of the participants, two bridge inspectors and one senior bridge inspector, confirmed that they had made use of RPAs for inspection purposes.

One bridge inspector (Participant 5) successfully utilised an RPA to gain access to restricted areas for project level inspection purposes of the Komati River Bridge. A 360° panoramic camera was mounted to the top of a DJI Mavic Pro to capture imagery of the deck soffit and bridge bearings. The RPA and camera were controlled independently by two operators, i.e., the RPA was operated by the pilot while the inspector controlled the camera. The participant confirmed that the method was successful and that the process worked very well in his opinion.

The second bridge inspector (Participant 17) obtained experience in utilising RPAs when the client requested the investigation of alternative methods to a UBIU to gain access to specific parts of a bridge. Some of the major issues experienced with the RPA were handling, controlling and flying underneath the bridge deck when signal was lost. Every time the RPA lost signal, it automatically returned to its take-off location. The initial objective was to use First Person View (FPV) goggles or a high-definition monitor on site to view the defects live. Based on this experiment, the participant was not convinced that inspectors would be able to identify and assess bridge defects. There were concerns about the inspectors' ability to gauge crack widths from photographs and video footage and whether the same results would be obtained from assessing bridges remotely using RPA footage compared to conventional methods.

The senior bridge inspector (Participant 9) worked with an independent firm that intended to utilise RPAs for inspections of approximately 30 bridges. The aim of the project was to inspect structural elements such as bearings and expansion joints where access was restricted. In most cases strong winds prevented the use of the RPA to complete the inspection. The bottom mounted camera used on the RPA could not sufficiently tilt upward to view the bridge bearings and it was largely decided that RPA inspections were not feasible. Another project where the use of an RPA was considered for safety and security reasons was at bridge sites in high-crime and dangerous areas. This project was unsuccessful due to technical complications with the RPA and the expiring of the operator's licence. The senior bridge inspector was of the opinion that even if these projects had been successfully completed, it would only have been proof of concept and the effectiveness of RPAs would still be unknown.

The remaining fifteen accredited inspectors that were interviewed had never made use of RPAs during structure inspections. The following key reasons were provided by the participants for not using RPAs:

- The time and cost required to train, procure and legally fly an RPA do not seem feasible at this stage for it to be used as a supplementary tool for bridge inspections.
- They were not familiar with RPA technology.
- RPAs are very expensive and not available or accessible at several companies.
- The inspection process could possibly take longer if both RPAs and conventional processes had to be followed.
- Several participants were aware of RPA limitations such as flying underneath a bridge and losing signal; restricted camera views; and weather conditions that could cause problems during the inspection, and therefore deemed it to be impractical and not feasible.
- While the RPA equipment and licensed operators were available within certain companies, the process required to obtain authorisation was extremely time consuming and would generally not be achievable within the anticipated budgets for network level inspections. It was however suggested that clients could either package approvals prior to the contract award, or a provisional sum could be made available to cover costs associated with this process.
- There were no available references or prior knowledge of successful implementation of this technology in South Africa.

Despite the participants' limited use of RPAs for bridge/culvert inspection purposes, they were all aware of and held opinions about utilising this technology for future bridge/culvert inspections.

5.2.6 Utilising RPA technology for future bridge inspections

The participants were asked to share their opinions about the possibility of using RPAs for future bridge inspection purposes. A rating system (see Table 5.3) was developed to show the likelihood of inspectors using RPAs based on their interview responses. A scale of 1 to 4 was used with the following criteria to assess and rate each response:

Table 5.3 Ratings and criteria to show the likelihood of participants using RPAs.

Rating	Likelihood	Criteria assigned to each rating value in terms of the likelihood of the inspector using RPAs for future inspections
4	High likely	Inspector is favourable towards the full use and integration of RPAs for bridge inspections
3	Likely	Inspector is positive about utilising RPAs for bridge inspections, but with limited use and application
2	Unlikely	Inspector is undecided but not opposed to the concept of RPA-assisted inspections
1	Highly unlikely	Inspector is mostly doubtful and disinclined towards the use of RPAs for bridge inspections

The culvert inspectors were largely undecided about using RPAs for inspection purposes, mainly due to RPAs lacking purpose during conditional assessment of culverts. They were however not opposed to the concept should it successfully reduce inspection times and make the process more efficient. Most of the bridge and senior bridge inspectors gave positive feedback on utilising RPAs for bridge inspections, but with limited use and application to large bridges only. The remaining bridge and senior bridge inspectors were either completely against or completely for utilising RPAs for future bridge inspections. The likelihood of culvert, bridge and senior bridge inspectors utilising RPAs for future bridge inspections is shown in Figure 5.4.

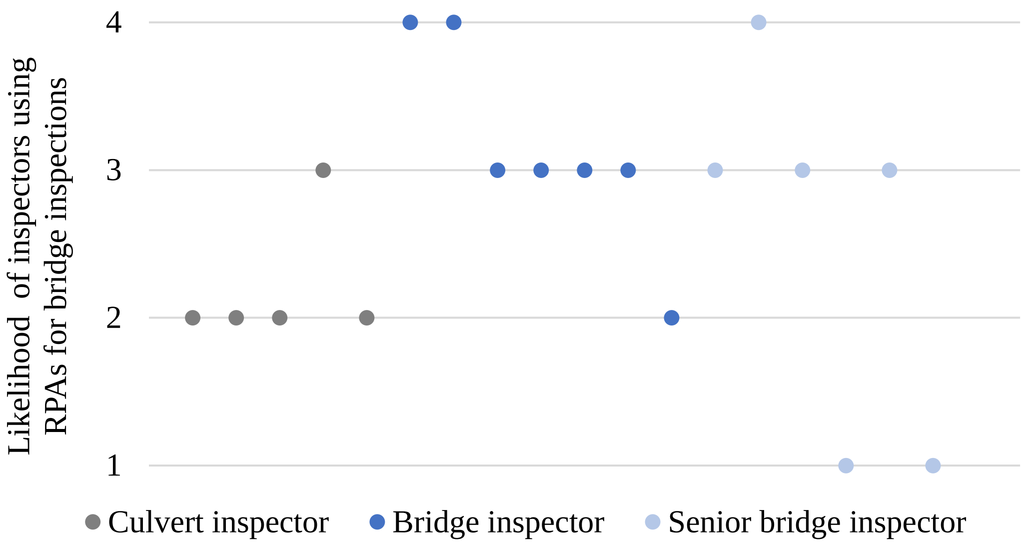


Figure 5.4 Likelihood of inspectors utilising RPAs for future bridge/culvert inspections.

Detailed responses of the inspectors are summarised in Table F1 (Appendix F), but the following key points were extracted from the interviews:

- RPAs could be used as a supplementary tool to capture inventory photos, fly over/along/under the structures and capture photographs/video footage of critical areas.
- There may be some application in using RPAs for bridge/culvert inspections, but it will not replace a comprehensive physical on-site inspection.
- RPAs could perhaps improve the quality of data where dense vegetation inhibits the inspection team from taking good quality photographs but will be restricted in the field to capturing only specific visual information.
- Using RPAs could save some time during the inspection process, especially for larger type structures, to capture photos of bearings and the underside of decks.
- There is merit in using RPAs for structures in areas with high vehicle traffic (i.e., bridges spanning multilane freeways) or very high/large structures with restricted access. Using RPAs for site flyovers is considered an effective approach to obtaining a good overall perspective of the structure and surroundings.
- Capturing inventory photographs and data could be achieved through well-trained technical staff (not necessarily the inspector). A two-phased process could be considered where the condition assessment and obtaining of inventory information is split.
- The successful implementation of RPAs for bridge inspections is doubtful and the accuracy of RPA-assisted inspections is of concern.
- There is merit is using RPAs for bigger bridges where a UBIU is required. RPAs could be used as opposed to a UBIU or binoculars in some bridge inspection applications.
- There are too many practical limitations such as flight time and reach and therefore RPAs are not a suitable tool for bridge inspection activities, according to some participants.

5.3 Chapter summary

The degree, extent and likelihood of using RPAs for bridge inspections in the Western Cape, South Africa were assessed by observations during the 2019 WCG principal bridge inspections, interviews with accredited inspectors from several reputable South African consulting engineering firms and interviews with RPA operators in the Western Cape.

During the personal observations, access and safety at the selected bridge sites and surroundings were evaluated to establish if RPAs could be used for specific inspection activities. Accredited bridge/culvert inspectors and RPA operators were interviewed to obtain and document their perspectives on and opinions about current bridge inspection practices as well as the use of commercially available RPAs for bridge inspection purposes.

Several aspects of conventional visual assessments and the TMH19 methods that were considered time consuming, costly and/or hindering the quality of data were identified during the observations and interviews.

The likelihood of culvert, bridge and senior bridge inspectors utilising RPAs for future bridge inspections was assessed. The participants were asked to share their opinion about the possibility of using RPAs for future bridge inspection purposes.

6 RPA platforms and components for bridge inspection activities

This chapter discusses the basic RPA platforms and their components which may be suitable for bridge inspection activities.

6.1 Selecting a fit-for-purpose RPA

The current RPA technology for corporate, commercial and personal use can be divided into three basic platforms - single/multi-rotor, fixed wing and VTOL unmanned aircraft. There are large variances within the RPA platforms in terms of use, weight, payload, price, size, and endurance. Table 6.1 shows the basic RPA platforms, their typical uses and consumer and professional grade examples.

Table 6.1 RPA platforms, common features and examples.

RPA platforms	Common features	Examples
Single/Multi-rotor or rotary wing (e.g., quadcopters, hexacopters, octacopters)	• Short flight durations of up to 35 minutes. • Able to vertically take off and land as well as hover in place at any time when required in flight. • Able to safely operate in confined spaces using obstacle avoidance technology and instant omnidirectional in-flight control.	**Consumer-grade:** DJI Mavic Mini; DJI Mavic Air; DJI Mavic Pro 2; DJI Phantom 4 Pro **Professional & commercial grade:** DJI Matrice 300 RTK; Freefly Alta 8; Flyabilty Elios 2; Skyfront Perimeter 8
Fixed wing	• Long endurance flights of up to 20 hours and operating link ranges of up to 250 km. • Faster flying speeds than multi-rotors. • Able to attach heavier and larger payloads compared to multi-rotors. • Cannot be operated in confined spaces. • Cannot hover in place. • Not typically equipped with obstacle avoidance technology due to restricted types of flight missions.	**Consumer-grade:** Yuneec Firebird FPV; Parrot Disco **Professional & commercial grade:** SenseFly eBee Classic
Vertical Take-off and Land (VTOL)	• The same as fixed wing; however, VTOL RPAs are capable of vertically take off and land and therefore launch and recovery equipment is not required. • Shorter/limited hover time.	**Consumer-grade:** Parrot Swing **Professional & commercial grade:** WingtraOne; Deltaquad Pro; Alti Reach (Pricing starts at R4.8 mil)

Each RPA platform has its own advantages and drawbacks. Fixed and VTOL RPAs can operate at higher speeds and with heavier payloads compared to multi-rotor RPAs but require thrust and lift, i.e., continuous forward motion, to keep the unmanned aircraft in the air. Multi-rotor RPAs have limitations in terms of payload capacity and range/mobility but can hover in place and fly in any direction (Shakhatreh, Sawalmeh, Al-Fuqaha, Zuochao, Almaita, Khalil, Othman, Khreishah & Mohsen, 2019).

Fixed and VTOL RPAs are therefore not suitable for flight missions in confined spaces. Multi-rotor unmanned aircraft are more suitable for bridge and culvert inspections due to their ability to operate in confined spaces and hover in place and their omnidirectional in-flight control.

Seo, Wacker and Duque (2018) identify several factors based on previous literature that need to be considered for selecting a suitable RPA for bridge inspection activities. Gillins *et al.* (2018) follow a similar approach to identify the required RPA characteristics for bridge inspections. These factors include a multi-rotor design, flight time, payload capacity and configuration, camera and video resolution, stabilising gimble, spotlights on the RPA, flight range, flight modes and flight planning software (manual and autonomous), sensor enhanced obstacle avoidance and in-flight first-person view. The affordability of the RPA is also an important factor for a cost-effective, feasible and wide-spread implementable alternative to conventional bridge inspection practices.

Darby, Hollerman and Miller (2019) used a qualitative approach to select a suitable commercially available (off-the-shelf) RPA for bridge inspection activities. This entailed using a panel of licensed RPA pilots, enthusiasts/hobbyists and engineering students to determine the evaluation criteria with a weighted ranking system. Their findings on selecting a suitable RPA for bridge inspections were largely in line with Seo, Wacker and Duque (2018) and Gillins *et al.* (2018).

These findings are collated and listed in Table 6.2 as key considerations for selecting a suitable RPA for network level bridge inspections.

Table 6.2 Key considerations for the selection of a suitable RPA for bridge inspection activities.

Key considerations
Ability to add optional payloads if required such as additional sensors, thermographers and LIDAR
The stability and resolution of the camera, i.e., electronic gimbal or automatic camera stabilisation, high-definition image capturing capabilities and the ability to use images for 3D models with photogrammetry
First-person view for the pilot and/or inspector to have a live view of the RPA camera view
Flight time of at least 20 minutes per battery charge and interchangeable batteries
Global Positioning Services (GPS) navigation enabled with automatic flightpath programming using 3D waypoints
RPA flight stability and enough range in strong winds
Capability of obstacle avoidance to avoid collision with the bridge components and surroundings and hover in place
The cost of the RPA

6.2 Remote pilot and flight crew component

A remote pilot means: "*the person who manipulates the flight controls or manages the flight command instructions of an RPA during flight time"* (SACAA). All unmanned flights require a remote pilot as he/she is responsible for planning the flight mission, operating the flight controls and issuing commands to the RPA prior to and during flights. The flight controls comprise a remote controller using radio frequency (i.e., the transmitter) that allows the remote pilot to communicate wirelessly to the RPA (i.e., the receiver). Radio frequency identification is used to pair the transmitter and receiver.

The remote pilot can use the flight controls to override the preloaded mission, operate and position the RPA and issue commands such as pausing/continuing with the preloaded mission, returning to the launch point, or landing. Remote pilots are often assisted by flight crew to ensure safer flight missions and operations.

A flight crew comprises visual observers and/or additional human operators to control the payloads and sensors. A visual observer is responsible for keeping continuous line of sight of the RPA and warning the remote pilot of anticipated dangers such as unsafe areas/locations or malfunctions that can be visually identified by someone other than the remote pilot. Additional human operators are sometimes used to independently control the payload, e.g., adjusting video and camera settings, pointing the camera and start/stop video recordings (Gillins *et al*., 2018).

6.3 Remote pilot station component

A remote pilot station means: "*the station at which the remote pilot manages the flight of the RPA"* (SACAA). This is also referred to as the control hub where the remote pilot launches, operates, monitors and controls the RPA and payload. For example, the RPA attitude (angle or tilt), altitude, speed and flight route can be determined and pre-loaded prior to take-off. During flight, the remote pilot uses the remote pilot station to monitor important information such as battery levels, pre-loaded settings, cameras, sensors, and the live location of the RPA. These settings can be pre-determined and specified for any flight mission. The RPA can also be controlled manually with a remote controller using radio frequency (long range) or Wi-Fi (short range). Most of flight planning software allows the remote pilot to pre-set and adjust camera settings (shutter, aperture, ISO, etc.) prior to and in flight (Gillins *et al*., 2018). Real-time footage such as video recordings and photographs can be sent wirelessly to the remote pilot station for on-site analysis by the inspector (Shakhatreh *et al*., 2019). The remote pilot station typically comprises a remote controller paired with a laptop using proprietary control software (Gillins *et al*., 2018).

6.4 Payload component

The payload is the weight that an RPA can transport. It refers to equipment that is temporarily or permanently fixed to the top or bottom of the RPA frame. The type of equipment used will mainly depend on the flight mission; however, the most common equipment are video cameras and red-green-blue imaging systems mounted on an electronic gimbal that is attached to the frame of the RPA. Gimbals can have two or three axes and are used to lessen vibrations, mitigate motion blur, and control the camera independently from the RPA. Other equipment includes infrared cameras, small lidar sensors, thermal cameras, additional sensors and data telemetry (Gillins *et al*., 2018). Small and lightweight multi-rotor RPAs have limited payload capacities which is a key challenge when heavy cameras and sensors are required for a flight mission (Shakhatreh *et al*., 2019).

6.5 Chapter summary

The purpose of this chapter was twofold: Firstly, to identify suitable and fit-for-purpose RPA platforms that could be used for bridge inspection activities in the Western Cape, when capturing inventory photographs and data for developing 3D models. Secondly, to describe the basic RPA components and their relevance to this study.

Three different RPA platforms were investigated and assessed in terms of their common features, advantages and drawbacks. There were large variances between the RPA platforms regarding use, weight, payload, price, size and endurance. Several key considerations were derived from previous studies and summarised (see Table 6.2) to simplify the selection process for a suitable RPA platform for bridge inspection activities. Based on the basic RPA components and key considerations, multi-rotor RPA platforms are best suited for bridge inspection activities and will be further discussed in Chapter 7.

It should be noted that the literature which identified key considerations for the RPA platform selection process did not differentiate between the use on a network level or project level bridge inspection (see Section 2.3.3). It is however assumed that if an RPA is suitable for project level inspections, it will also be suitable for network level inspections.

7 RPA test flights at selected bridge sites

In this chapter, the selected two bridge sites and the RPA platforms, technical findings and analysis of the field data are discussed in depth. The selected bridge sites are White Bridge and Benning Bridge. A different RPA platform and flight planning approach was used at each bridge site. The results from the two bridge sites and the two RPA platforms are analysed and compared in terms of the fight planning required, inventory photographs, cost and photogrammetry models.

Two independent remote pilots were used to operate their own RPAs to ensure compliance in terms of the SACAA rules and regulations (see Section 2.2). Both remote pilots that performed the flight missions for this study had no prior experience in performing bridge inspections. However, the TMH19 inventory photograph requirements were explained to the remote pilots at the bridge sites. Example images of the required inventory photographs were discussed and shown to the remote pilots for background purposes and ease of reference.

The location of both bridge sites was checked to ensure that no additional authorisations or permissions were required for legal and safe RPA operations. It was confirmed that both bridge sites were not located within any protected/controlled/restricted airspace, airports or no-fly zones, as discussed in Section 2.2. An example of an approved application is shown in Appendix G2.

Both structures are used daily by the public and carry high volumes of traffic. Therefore, using these bridge sites as case studies provided real-world examples to test the use, performance and feasibility of RPAs for bridge inspection activities and the potential future implementation of this technology on a network level. Both RPA platforms were tested and flown successfully at the selected bridge sites.

7.1 Selected bridge sites for RPA-assisted bridge inspections

This section describes the location, geometry and logistics of two large river bridges in the Western Cape, namely White Bridge near Knysna and Benning bridge near Gordons Bay. Several challenges were experienced at each site while testing the two different RPA platforms. White Bridge served as a case study to test the use, performance and feasibility of a DJI Mavic Mini. Benning Bridge served as a case study to test the use, performance and feasibility of a DJI Phantom 4 Pro.

7.1.1 White Bridge (Western Cape Provincial Bridge No. B1420)

White Bridge (see Figure 7.1) is located on the N2 near Knysna, Western Cape, and crosses the Knysna lagoon. The bridge consists of two independent prestressed concrete decks with a total length of 164.92 m and a total combined width of 17.85 m. As the bridge exceeds 100 m in length, it is classified as a very large bridge (see Figure 4.3). The original bridge was constructed around 1952 and widened through the construction of a second adjacent bridge in 1987. The superstructure of the bridges consists of a two-separate cast in-situ, five-span continuous prestressed concrete deck with half-lap joints in spans S1, S3 and S5. A longitudinal joint along the centreline of the opposing traffic lanes separates the two bridge decks. The substructures of both bridges are cast in-situ and consist of reinforced concrete spill through abutments and solid walled piers. The clearance above the tidal lagoon is approximately 7.5 m. Major bridge repairs were undertaken in 2003.

Figure 7.1 North view of White Bridge (DJI Mavic Mini, photo taken by Mr C. Jurgens).

The latest principal inspection was completed in July 2020, approximately 17 years after the bridge repairs had been done. A thorough inspection of all the spans could not be completed because a boat or UBIU was not available to provide access to the bridge decks (S2, S3, S4) spanning the lagoon. The lack of availability of access equipment was due to the Coronavirus disease (COVID-19) lockdown restrictions at the time of inspection. As a result, this bridge provided an excellent opportunity for testing the use, performance and feasibility of an RPA. No accommodation of traffic was needed, as the RPA did not fly directly over the public road.

The DJI Mavic Mini (see Section 7.2.1) was the only RPA platform that was used for bridge inspection activities at this site. Although the remote pilot deemed the clearance under the bridge adequate for safe operation, the centre spans of the bridge would have required the RPA to fly Beyond Visual Line of Sight (B-VLOS). A special permit is required for B-VLOS operations which fall outside the scope of this study. Despite this limitation, the imagery of the bridge soffit using the gimbal upward tilt function and the imagery of the top and sides of the bridge yielded enough information for analysis purposes.

7.1.2 Benning Bridge (Western Cape Provincial Bridge No. B2604)

Benning Bridge (see Figure 7.2) is located along the coast on the R44 near Gordons Bay, Western Cape, and crosses the Steenbras River mouth. The bridge consists of reinforced concrete arches jointed with crossbeams, two main piers and spandrel columns supporting the reinforced concrete deck. The total width of the bridge is 7.62 m, and the total length of the bridge is 65 m; it’s therefore classified as a large bridge (see Figure 4.3). The bridge was built in 1935. Major bridge repairs were undertaken in 1999. The bridge was again identified by the WCG DTPW as a structure requiring urgent maintenance and was inspected by a consulting engineering firm in 2009.

Figure 7.2 North view of Benning Bridge (DJI Phantom 4 Pro, photo taken by Mr W. Witte).

The latest principal inspection was completed in November 2019, approximately 10 years after the project level inspection. The 2019 principal inspection report highlighted some damage to the structure such as concrete spalls and corrosion.

This bridge was used to test the DJI Phantom 4 Pro platform (see Section 7.2.2). The clearance above the river at the highest point of the arch is approximately 14 m, making it a good test site to safely navigate and fly under the structure to collect imagery of the deck soffit, arches and crossbeams.

7.2 RPA platforms investigated

Two RPA platforms, namely the DJI Mavic Mini and DJI Phantom 4 Pro, were tested and compared in this study. Several metrics were used as part of the comparison to give an overview of the benefits and challenges of each platform (Tables 6.2 and 7.1). As the high-resolution camera is the primary sensor used to collect visual data, the camera stability, sensor size, exposure and resolution were important factors to consider. The tested platforms were off-the-shelf RPAs with no additional alterations or modifications.

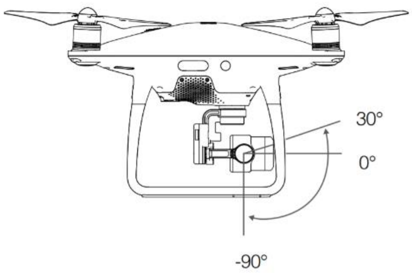
The benefits of using commercially available RPAs for bridge inspection activities are:

- A variety of options are available at competitive pricing.
- Off-the-shelf RPA hardware/software have already been developed and tested. Therefore, no additional research and development costs are involved.
- Proprietary software and firmware updates are available for as long as the products are supported.

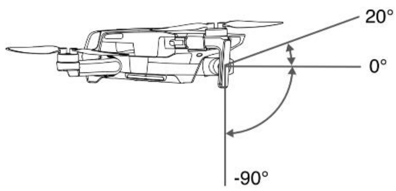
It should be noted that any activity that requires physical hands-on investigations such as a sounding survey using a hammer cannot easily be achieved with an off-the-shelf UAV due to payload restrictions. Furthermore, most cameras currently found on commercially available RPAs are mounted to the bottom of the RPA body, which restricts taking photographs of the deck soffit or detailed photographs of bridge bearings. The effect of this restriction is discussed in Section 7.3.

Table 7.1 Comparison between the RPA platforms tested for bridge inspection activities.

Metrics	**DJI Mavic Mini**	**DJI Phantom 4 Pro**
		
Additional payloads	No	No
Camera stability (gimbal)	3-axis (tilt, roll, pan)	3-axis (tilt, roll, pan)
Resolution (MP)	12	20
Camera sensor (inch)	1/2.3	1
Obstacle sensing	Downward	Front & Rear Left & Right Infrared Downward
First person view	Yes	Yes
Flight time (minutes)	+/- 30	+/- 30
Flightpath programming	No	Yes (waypoints)
Flight stability viz. wind resistance (m/s)	8	10
Weight (grams)	249	1388
Dimensions (millimetre)	Unfolded with propellers: 245×289×55 (L×W×H)	With propellers: 305x350x190 (L×W×H)
Price (ZAR)	R 9000.00	R 35 000.00



(a) DJI Phantom 4 Pro gimbal tilt range (DJI, 2016)



(b) DJI Mavic Mini gimbal tilt range (DJI, 2019)

Figure 7.3 Gimbal tilt range.

The gimbal tilt range of the Phantom 4 Pro and Mavic mini is 30 degrees and 20 degrees, respectively, as shown in Figures 7.3 (a) and (b). This function enables the camera to rotate upward to capture images of the bridge deck, substructure and bearings if there is enough clearance. Sample images are shown in Figures 7.4 (a) and (b) taken at the selected bridge test sites using the gimbal tilt function.

(a) Sample image of the Benning bridge deck soffit and substructure captured with the DJI Phantom 4 Pro

(b) Sample image of the White bridge deck soffit and substructure captured with the DJI Mavic Mini

Figure 7.4 Sample images using the RPA gimbal tilt function.

7.2.1 DJI Mavic Mini

The DJI Mavic Mini is a compact and easy-to-fly RPA with a three-axis motorised gimbal and a high-resolution camera mounted to the front of the RPA body (see Table 7.1). Some of the biggest benefits of this platform are the camera performance, flight time and low initial investment cost. The lightweight platform allows for precise control and manoeuvrability under and around bridges; however, due to the lack of adequate obstacle sensing and avoidance technology, it is more susceptible to collisions and/or accidents when the remote pilot loses control and/or when high windspeeds are encountered during flight. The platform comes standard with an attachable propeller guard that improves flight safety.

The platform can hover in place using its downward vision positioning and infrared sensing technology. It provides a +/- 0.5 m vertical and +/- 1.5 m hovering accuracy range with GPS positioning. It does however require adequate lighting and non-reflective surfaces to accurately hover in place. The remote controller can maintain a 4 km range for streaming high definition (HD) 720 p video feed to the remote pilot's mobile device. The mounted camera supports 12 MP photographs and 2.7 K HD video recordings.

The images and video recordings taken at the bridge test site were high quality and clear due to the motorised stabilisation. However, due consideration should be given to the time of day that inspections are conducted to ensure that the camera exposure settings are correct. Figure 7.5 shows under/overexposed samples of unfiltered and unedited Joint Photographic Experts Group (JPEG) images collected between 15:00 and 16:00 on 6 July 2020 at White Bridge.

(a) DJI Mavic Mini underexposed photograph: Image appears too dark

(b) DJI Mavic Mini overexposed photograph: Image appears too light

Figure 7.5 Sample images of under- and over-exposed photographs captured by a DJI Mavic Mini.

Important visual detail is lost in poor-quality photographs which generally result in additional time required for either post-editing or recapturing of images. It is therefore important that the remote pilot has a basic understanding of dynamic range, how exposure works, and how to control the camera shutter speed, settings to adjust the photograph brightness and aperture settings. Shakhatreh *et al.* (2019) found that RPA camera settings, specifically the camera shutter speed, must be adjusted for the flight mission according to the diverse lighting conditions that will be encountered. If the shutter speed exposure time is too short, the photographs might be too dark and not usable in terms of distinguishing between key features or aspects that were captured; if the exposure is too long, the photographs may be blurry or too bright.

The Mavic Mini User Manual states that it only allows for additional accessories with a maximum weight of up to 30 grams, e.g., the attachable propeller guards. This platform does not allow for customisation if required for bridge inspection activities as it is not designed to retrofit additional sensors or payloads.

No published literature or research was found where a DJI Mavic Mini was used or tested for bridge inspection purposes.

7.2.2 DJI Phantom 4 Pro

The DJI Phantom 4 Pro is a medium-sized RPA platform. The rated flight time of the Phantom 4 Pro is similar to that of the Mavic Mini at approximately 30 minutes but it offers additional features such as vision and infrared obstacle sensing, programmable autonomous flights, and dual frequency support for efficient and stable HD video downlink. Like the Mavic Mini, this platform does not allow for customisation and no additional sensors or payloads can be accommodated on this RPA. The platform specifications that are relevant to this study are shown in Table 7.1.

The obstacle sensors enable this platform to mitigate collisions and actively avoid obstacles during flight. There are vision positioning sensors in the forward, backward and downward direction to assist the remote pilot to safely operate the RPA in areas where GPS signal is limited or unavailable. Infrared obstacle sensors are on both sides of the platform. Infrared and ultrasonic sensors are standard at the bottom of the platform. The obstacle sensing capability is significantly more advanced than that of the Mavic Mini which only offers downward sensors; however, the Phantom 4 Pro cannot detect obstacles above the RPA due to the lack of upward-facing sensors. Test flights showed that with enough clearance between the RPA and the bridge soffit, the remote pilot was able to safely operate the RPA under a bridge and in GPS-deprived areas.

The 20 MP camera that is mounted on a motorised gimbal supports real-time remote viewing of images through the DJI downlink technology. This enables the remote pilot to concentrate on flying the RPA while the inspector can view images, observe defects and make decisions if required during the inspection flight as opposed to post-flight analysis of data.

The DJI Phantom RPA range is widely researched and used in several studies for bridge inspection purposes, including: Evaluating the use of drones for timber bridge inspection by Seo, Wacker and Duque, 2018; A Practitioner's Guide to Small Unmanned Aerial Systems for Bridge Inspections by Dorafshan, Thomas, Coopmans & Maguire, 2019; A Streamlined Bridge Inspection Framework utilizing Unmanned Aerial Vehicles by Perry, 2019; Fatigue Crack Detection Using Unmanned Aerial Systems in Under-Bridge Inspection by Dorafshan, Maguire, Hoffer & Coopmans, 2017; and UAV Bridge Inspection through Evaluated 3D Reconstructions by Chen, Laefer, Mangina, Zolanvari & Byrne, 2019.

7.3 Flight methods

Two different flight methods were used to operate and fly the DJI Mavic Mini and the DJI Phantom 4 Pro around the bridge sites. The flights at White Bridge were completely manually controlled (method 1) while the flights at Benning Bridge were autonomously and semi-autonomously flown (method 2). Semi-autonomous flights refer to a hybrid approach between manually and autonomously controlled flight. Both methods have advantages and constraints. Two main flight missions were planned and performed at each bridge site; they included:

- Capturing inventory photographs as per the TMH19 requirements
- Capturing detailed photographs to develop 3D digital models.

The actions completed prior to, during and after the RPA test flights at the selected bridge sites are shown in Figure 7.6. These actions were developed from literature (Gillins *et al.*, 2018; Dorafshan *et al.*, 2019; Shakhatreh *et al.*, 2019).

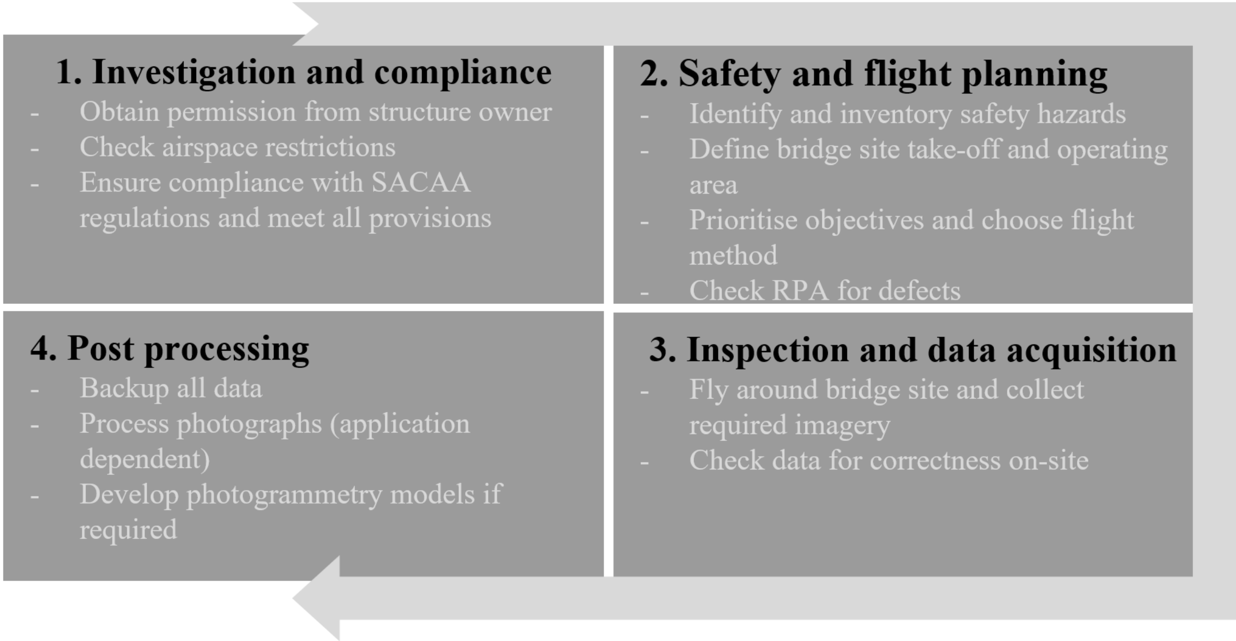


Figure 7.6 Actions completed prior to, during and after RPA test flights at selected bridge sites.

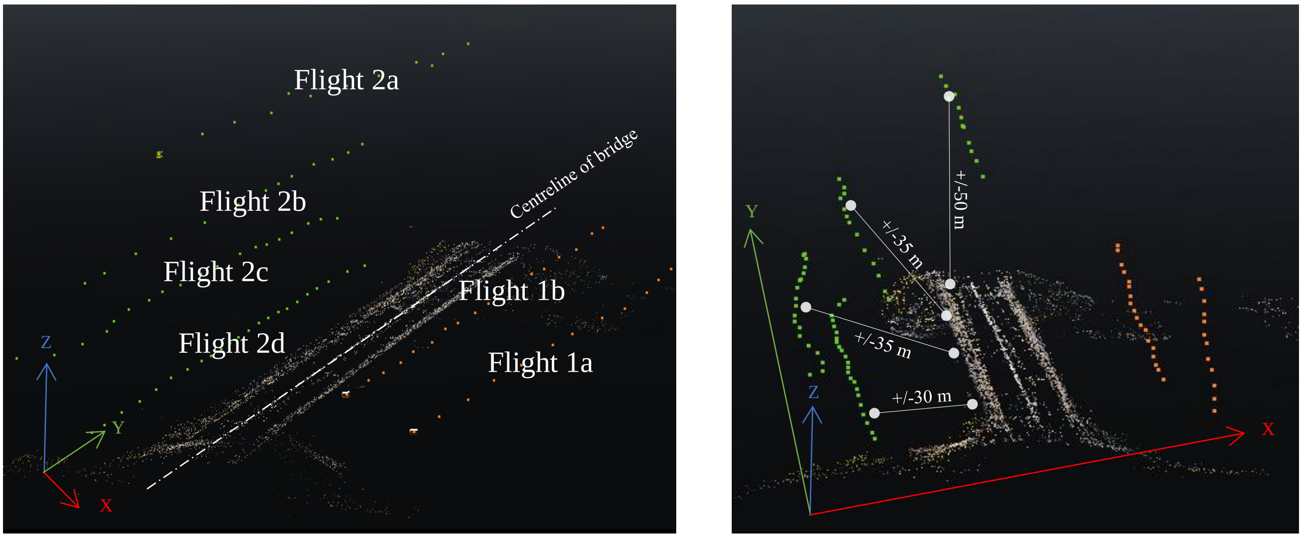
7.3.1 Flight method 1: Manually flying a DJI Mavic Mini at the White Bridge site

In this method, the RPA is flown manually using only the control sticks (direction and throttle levers) on the Remote Controller, giving the remote pilot full control of the RPA. This method allows for full navigational control and manoeuvrability of the RPA in addition to taking photographs and videos as required.

A Google Earth aerial image of White Bridge was used to visually show the approximate RPA positions in line with the TMH19 view descriptions for each inventory photograph (see Figure 7.7). The shortest flight path between the viewpoints was drawn using linear lines and adjusted on site based on the size of the structure, standoff distance required in terms of the camera focal length, camera orientation, and flying height/altitude. The exact position of the RPA for each inventory photograph was finally determined during flight through monitoring the live video feed (through a digital downlink) on the mobile device’s screen to compose each shot. The photographs were taken during two separate flights on either side of the bridge to avoid flying over live traffic. Close-up photographs of the bridge joints and bridge number were manually taken by using the RPA as a handheld camera.

Figure 7.7 Proposed RPA positions for capturing inventory photographs

The manual flight method used to capture images for the development of a 3D model entailed flying the RPA parallel to the centreline of the bridge (Y-direction) at a fixed offset and altitude per flight (see Figure 7.8). Two flight missions consisting of six flight paths were performed, and photographs were manually taken at the following approximate horizontal intervals at a fixed offset and altitude: flight 1a – 14 m; flight 1b – 9 m; flight 2a – 14 m; flight 2b – 13 m; flight 2c – 9 m; flight 2d -7 m.



(a) Number of and sequence of manual flights

(b) Manual flights offsets to bridge

Figure 7.8 Manually flown RPA flightpath to perform 3D reconstruction from photographs of White Bridge.

The DJI Mavic Mini was able to keep a consistent altitude for each flight due to the active GPS positioning system and a strong GPS signal. The manual test flights however presented several problems. The wind had a major influence on the stability of the small RPA in the horizontal direction. As a result, the remote pilot was not able to keep the RPA at a consistent offset (X-direction of flights 1 and 2 as shown in Figure 7.8 (b) from the bridge. The remote pilot tried to counter the effects of wind during flights 2c and 2d by manually adjusting the RPA relative to the bridge. Trying to correct the offset manually resulted in a non-linear line of flight with varying distances relative to the side of the bridge. The wind did not have a negative effect on image quality (X-direction of flights 2c and 2d as shown in Figure 7.8), but it did affect the constancy of overlapping of the images for photogrammetry purposes.

Successful acquisition of data using *flight method 1* is therefore mainly based on the remote pilot's understanding of the flight mission and his or her ability and skills to operate the RPA and camera around the bridge site. This approach is therefore not recommended, as it is subjected to the remote pilot's ability to execute the flight mission.

7.3.2 Flight method 2: Autonomously and semi-autonomously flying a DJI Phantom 4 Pro at the Benning Bridge site

Two consumer-grade software platforms (DroneDeploy and Pix4DCapture) were used to create flight plans to fly the DJI Phantom 4 Pro autonomously and semi-autonomously at the Benning Bridge site. Both platforms offer the possibility to fly diverse kinds of flight missions, including single grids, double grids, polygonal, circular and free flights.

A single grid autonomous flight mission refers to a set of flights in the shape of a rectangle. A double grid autonomous flight mission refers to two sets of flights in a rectangle shape flown perpendicularly to each other during the same flight. Single grid flights are typically used to survey large, relatively flat areas with the main interest of creating 2D maps. Double grids are typically used for small and medium-sized areas with height fluctuations and/or vertical objects with the main interest of creating 3D models. A polygonal autonomous flight mission is used when the environment requires a flexible boundary (other than a rectangle), while a circular autonomous flight is used to obtain imagery of a small area flown in an ellipsoid motion around an isolated object. Similar to circular autonomous flights, free flights are typically used to obtain imagery of a surface or object consisting of a small area, but the flight path is manually controlled by the remote pilot and is completely flexible in both the horizontal and vertical planes (Pix4D, 2017). Semi-autonomous flights refer to any autonomous flight combined with free flight during the mission.

Grid and polygonal flights are flown at a fixed altitude for the entire flight mission; the RPA elevation cannot be changed during the pre-set mission. Although grid flights are useful for creating digital elevation models, a change in altitude is needed for bridge inspection activities to obtain imagery of the substructure and deck soffit. A circular flight mission does allow for a change in elevation during flight, but it is limited to pre-set conditions such as flying in an ellipsoid motion around an isolated object while changing elevation (Pix4D, 2017). A circular flight mission may be useful for large chimneys, towers or buildings, but the use is limited for bridge inspection activities due to the geometry difference at bridge sites and the varying terrain (Gillins *et al.*, 2018; Perry, 2019).

(a) Single grid autonomous flight mission

(b) Double grid autonomous flight mission

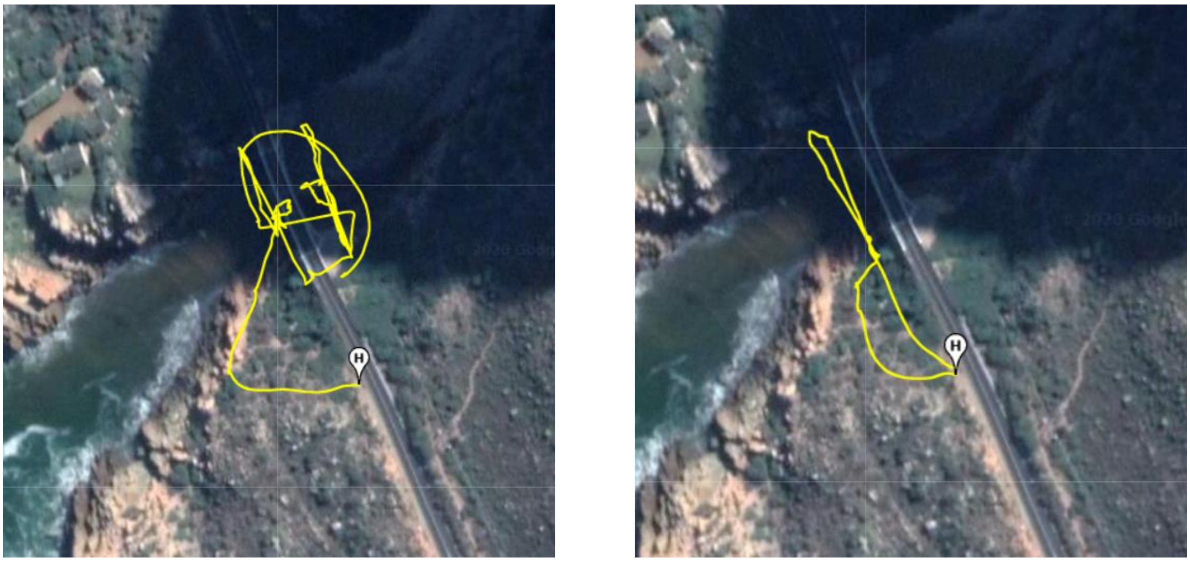
Figure 7.9 Single and double grid autonomous flight missions at Benning Bridge.

The flight mission software image acquisition plan ensures that photographs are taken with sufficient overlapping for optimal processing to cover the entire area of the mission or point of interest (Shakhatreh *et al.*, 2019). Sufficient overlapping means that each part of the subject is photographed from three or more distinct viewpoints for the development of 3D digital models. Image processing software such as Bentley ContextCapture recommends an overlap of at least two thirds (66.67%) between consecutive photographs. Pix4DMapper offers more detailed image acquisition plans depending on the object and terrain to be reconstructed (Pix4D, 2015).

For optimal results, the correct type of flight mission or combination of flight missions and the image acquisition plan must be selected depending on the bridge site (i.e., structure and terrain) that needs to be reconstructed as a digital 3D model.

At Benning Bridge, the remote pilot used a mobile device to create a single grid (see Figure 7.9 (a)) and a double grid (see Figure 7.9 (b)) flight mission on site using both the DroneDeploy and Pix4DCapture mobile applications. After the grid flight missions had been uploaded, the RPA was able to automatically take off, fly the grid missions, capture imagery at specified intervals and land at the take-off position without any intervention from the remote pilot. As the grid flight missions were limited to fixed elevations, additional free flight missions (see Figures 7.10 (a) & (b)) were conducted to capture the required TMH19 photographs as well as additional imagery for the development of more detailed 3D models.

For safety and ease of use during the free flight missions, software applications such as Pix4DCapture allow the remote pilot to fly manually but capture images automatically. The software offers default settings for the vertical and horizontal image spacing to capture photographs at a specified distance from the object to be digitally reconstructed. The digital 3D models of Benning Bridge are discussed in Section 7.5.



(a) Free flight mission 1

(b) Free flight mission 2

Figure 7.10 Free flight missions to capture detailed imagery of the bridge substructure, deck soffit, and the required TMH19 photographs (https://app.airdata.com).

The flight logs of the free flight missions can be downloaded, saved and reused for future flights with the purpose of saving time through repeating the same flight path. This could be used for recapturing TMH19 inventory photographs for future bridge inspections, tracking changes at the bridge site and monitoring structure health. Furthermore, third party software such as AirData UAV offer valuable RPA flight performance information when flight logs are uploaded to their platform (see Appendix G).

(a) Remote Pilot and flight crew

(b) Remote Pilot and RPA

Figure 7.11 Remote pilot and flight crew at Benning Bridge.

Flight method 2 is only possible for RPAs with the functionality to undertake autonomous flight missions. The remote pilot and flight crew (see Figures 7.11 (a) & (b)) are still required to understand the flight mission and be able to operate an RPA and the mounted camera around the bridge site during free flight. The free flight part of the mission is essential for the development of detailed 3D models.

8 Discussion of results

8.1 Quality of inventory photographs

Collecting inventory data by using an RPA rather than a handheld digital camera (conventional human-based method) is very different, but both processes offer specific advantages and drawbacks. In the conventional method of taking photographs the bridge inspector or technical assistant walks around the bridge site with a handheld digital camera for capturing and collecting the required data. When using an RPA, the remote pilot remains stationary while the RPA flies around the bridge site to collect the required data. The two processes are compared in terms of image quality and duration in this section.

Since RPAs can fly over physical obstacles such as fencing, vegetation, high fills and steep embankments, the RPA can travel around the entire bridge in a short amount of time while collecting a large amount of data, whereas with the conventional method, the time needed to collect the data is based on the actual terrain and the ability of the inspector/technical assistant to get to the desired positions for capturing inventory imagery with a handheld digital camera. Because the use of RPAs is affected by weather conditions and governed by strict legislation, there are critical additional factors to consider when compared to conventional methods, which merely requires walking on site. Walking is however time consuming, especially at large bridges or inaccessible areas, and sometimes unsafe due to difficult terrain and traffic.

The only equipment required to obtain inventory photographs through the conventional method is a GPS-enabled handheld digital camera (TMH19 requirement). The GPS function allows for photographs to be geotagged. This enables the BMS software to georeference the collected photographs to real-world coordinates and to visually display the positions on a map. Using an RPA, however, can be more expensive due to the costs involved in its initial procurement and future maintenance as well as training or hiring a licensed remote pilot and flight crew. Prior to the actual bridge inspections, additional time is required to obtain the approvals and authorisations needed to fly an RPA at the selected bridge sites. Once all legislative provisions are met, an RPA offers the advantage of safe, fast and repeatable data acquisition.

To obtain the inventory photographs at White Bridge, the DJI Mavic Mini was tested, and the results were compared to the photographs collected by the conventional method (see Section 8.1.1). The same approach was followed at Benning Bridge using the DJI Phantom 4 Pro (see Section 8.1.2).

The evaluation criteria shown in Table 8.1 were applied to compare the image quality of the inventory photographs collected with an RPA versus a handheld digital camera. Each criterion was assigned a rating of good (2 points), fair (1 point) or poor (0 points) for each photograph. The completed evaluations for each photograph and subset of photographs may be viewed in Appendix H and are discussed in Section 8.1.1 and Section 8.1.2.

Table 8.1 Evaluation criteria and rating system for inventory photograph quality.

Criteria	**Good**	**Fair**	**Poor**	**Comments**
Composition *Photograph meets the view description as outlined in TMH19, framed correctly, and no distracting elements that could have been avoided.*				
Lighting *Photograph not over- (too light) or under- (too dark) exposed.*				
Focus *Photograph is not blurry.*				
Overall impression *Photograph provides the required and additional perspectives and adds value.*				

The duration of time for collecting the inventory photographs was measured between the time when the first and the last photographs were taken. The duration of the initial setup and close-out activities was excluded due to its subjectivity and for uniform comparison. The times used for calculating the durations were extracted from the photograph Exchangeable Image File Format data. The results of the durations for both processes to collect inventory photographs are shown in Figure 8.1.

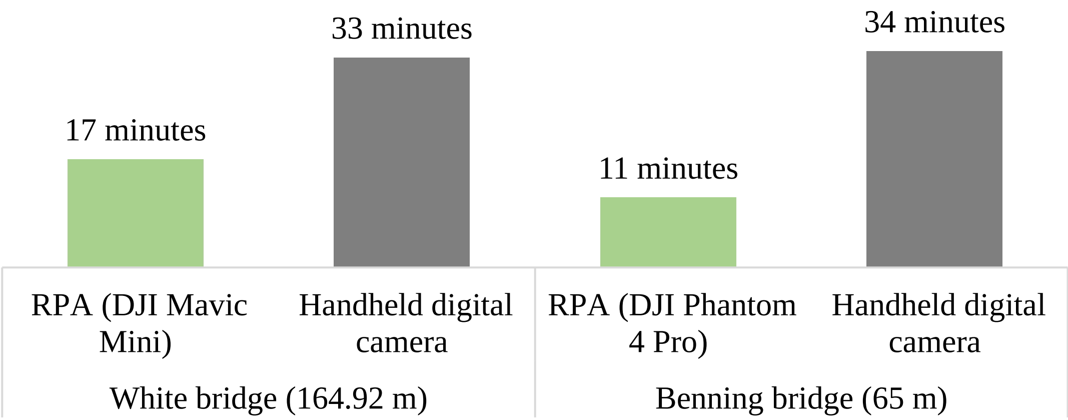


Figure 8.1 Time spent collecting inventory photographs at White Bridge and Benning Bridge.

By using the DJI Mavic Mini at White Bridge, the collection of inventory photographs was 48% (16 minutes) faster than the conventional method of using a handheld digital camera. A similar outcome was achieved at Benning Bridge, where the use of an RPA (DJI Phantom 4 Pro) was 68% (23 minutes) faster than the conventional manual method.

The duration difference between the RPA platforms at the two bridge sites may be attributed to the type of RPAs used, the flight method (autonomous versus manual flight), the bridge sizes, the experience of the remote pilot and the weather conditions. The duration of time to collect inventory photographs at both bridge sites by conventual handheld digital cameras was approximately the same, despite White Bridge (a very large bridge) being two and a half times longer than Benning Bridge (a large bridge). The prolonged data collection times at Benning Bridge were attributed to the dense vegetation and steep embankments, making it difficult, unsafe and time consuming for the bridge inspector and technical assistant to reach several of the required positions for collecting the inventory photographs.

The time required to collect inventory photographs through an RPA can be further reduced during repeat flights. The first flight will always consume more time at any bridge site, as the remote pilot has to ensure the correct position, orientation and composition of each inventory photograph. If this is done correctly during the first missions, the flight paths can be saved, and the missions and collection of photographs can be automatically repeated as and when required.

8.1.1 Comparison of a DJI Mavic Mini and a handheld digital camera to obtain inventory photographs

Two subsets of inventory photographs were collected at White Bridge using a DJI Mavic Mini (see Figure 8.2) and a conventional handheld digital camera (see Figure 8.3). The number shown at the top left corner of each subset photograph refers to the actual inventory view descriptions in the TMH19 (Appendix D). Inventory views 12, 13, 14 and 16 were not included in the interest of report brevity and relevance.

Based on the evaluation criteria, the overall photographs collected with the DJI Mavic Mini yielded the same or better-quality images than the handheld digital camera. Photographs of views 1, 2, 3, 4, 7, 8 & 11 collected with the RPA were rated higher than the equivalent photographs collected by the handheld digital camera. The aerial photography also allows for a holistic birds-eye view of the bridge site which provides additional perspective not otherwise possible. The RPA is not limited by the physical terrain of the bridge site, and therefore distracting elements such a tree or difficult terrain can easily be avoided. Photographs of views 5, 6, 9 and 10 were rated equal in quality, while view 15 was rated higher in favour of the handheld digital camera. Using an RPA as a handheld camera (see view 15) constrains the remote pilot to view the shot composition on the mobile device with his/her one hand while physically pointing the RPA camera where required with his/her other hand.

Figure 8.2 Subset of inventory photographs collected with a DJI Mavic Mini at White Bridge.

Figure 8.3 Subset of inventory photographs collected with a handheld digital camera at White Bridge.

8.1.2 Comparison of a DJI Phantom 4 Pro and a handheld digital camera to obtain inventory photographs

Following a similar approach as outlined in Section 8.1.1, two subsets of inventory photographs were collected at Benning Bridge using a DJI Phantom 4 Pro and a conventional handheld digital camera, as shown in Figure 8.4 and Figure 8.5, respectively.

Photographs of views 1, 5, 6, 7, 8, 10 and 11 collected with the RPA were rated higher for the same reason provided in Section 8.1.1. Photographs of views 2, 3, 4 and 15 were rated equal in quality, while view 9 was rated higher in favour of the handheld digital camera. The tilt function of the gimbal (see Section 7.2) provided a limited view of the deck soffit and although considered sufficient, the conventional method yielded better perspective of this view.

Figure 8.4 Subset of inventory photographs collected with a DJI Phantom 4 Pro at Benning Bridge.

Figure 8.5 Subset of inventory photographs collected with a handheld digital camera at Benning Bridge.

8.2 Quality of photo-realistic three-dimensional (3D) bridge models

Three-dimensional (3D) bridge modelling has been introduced and widely researched in numerous studies as a technology with the potential to disrupt current bridge inspection and bridge management practices. The integrated use of 3D bridge models with other applications such as Building Information Modelling (BIM) and damage detection algorithms allows for manual and automated identification of bridge components and defects, quantification of defects/damage, dimensional surveys, and GIS interoperability by means of a safer and more economical approach to acquiring the data (Chan, Saul, Pettigrew & Anstice, 2017; Chen *et al.*, 2019; Jeong, Seo & Wacker, 2020; Perry *et al.*, 2020; Duque, Seo & Wacker, 2018).

The above studies are mainly based on detailed project level inspections and proof of concepts and do not provide implementable and/or sustainable solutions for developing and using 3D bridge models on a network level. The purpose of this research was to investigate how 3D models could be developed by using commercially available off-the-shelf RPAs for extracting inventory data and conducting virtual safety inspections on a network level. As network level inspections are performed at frequent intervals for thousands of structures, it is important to minimise data, on-site time, and the computation time required to develop and effectively use the 3D bridge models for inventory acquisition and safety inspection purposes.

In this study, four 3D bridge models were created using photographs acquired during the RPA flights as discussed in Section 7.3. The DJI Mavic Mini and the DJI Phantom 4 Pro were used for the photograph acquisition at White Bridge and Benning Bridge, respectively. The steps applied to assess the 3D bridge models for their usefulness on a network level were:

1. Visually checking the 3D bridge models for completeness by focusing on the main bridge components such as the deck roadway, deck soffit, balustrades, piers, abutments and embankments. If the bridge components were successfully developed, the next step was actioned. If two or more of the bridge components were unsuccessfully developed, the 3D model was discarded, and the process used to acquire the photographs was deemed unsuccessful.
2. Extracting inventory data and populating the standard TMH19 inventory sheets and verifying the accuracy against the 2019 BMS inspection results.
3. Conducting a virtual safety inspection in line with the CR2014 provisions.

One important aspect to note when creating digital 3D objects using 2D photographs is the reconstruction of uniform, non-static (i.e., moving) and reflective surfaces (such as water) due to the difficulty of finding matching key points between consecutive photographs. ContextCapture does provide two solutions to correctly recover water surfaces in georeferenced models, namely the Geometry Constraints Method and the Reconstructive Constraints Method. The former process extracts water surfaces from a Keyhole Markup Language (KML) file produced in third party software, while the latter process automatically detects and reproduces water surfaces through an Artificial Intelligence (AI) compatible Graphics Processing Unit (GPU). For the purposes of this study, the reconstruction of water surfaces is considered irrelevant in terms of extracting inventory data from the 3D models.

Safety inspections, also referred to as monitoring inspections, may be carried out by less experienced personnel because the information that is required has reference to existing inspection data (Nordengen & De Fleuriot, 1998). Therefore, detailed 3D bridge models offer a potential new way to enhance the effectiveness of these inspections. Less experienced inspection teams can complete the field surveys and collect enough data for the development of 3D bridge models which can be verified in-office by accredited bridge inspectors. The TMH19 inspection items assessed during the virtual inspection included waterways, foundations, substructures, bearings, bridge decks, expansion joints, drainage and safety features such as the parapets, guardrails and handrails.

Currently, there are several options of image-based 3D modelling software to choose from such as Autodesk ReMake, PhotoSynth, ContextCapture and PIX4DMapper. ContextCapture, developed by Bentley Systems, was used in this study as WCG DTPW has a usage agreement and licensing with Bentley Systems. ContextCapture is image processing software that automatically reconstructs objects from imagery datasets collected by, but not limited to, RPAs. The reconstructed objects, also known as 3D models, can be converted into terrain models, a mesh or a point-cloud.

ContextCapture follows a specific workflow to produce 3D models from photographs. Firstly, photographs are imported, and the camera properties are verified. If the camera properties are not automatically identified from the software database of camera definitions, the user will have to enter the sensor size, focal length, and the 35 mm equivalent. Thereafter, the photographs are oriented in 3D space, exactly where the camera was when each photograph was taken. The software automatically identifies and triangulates the same features found on three photographs as a minimum to determine their position to one another in 3D space. This process is called aerotriangulation. After the completion of aerotriangulation, the reconstruction settings must be adapted for accurate placement of the data to match the real world and to adjust the spatial framework for identifying and eliminating irrelevant data with respect to the point of interest (e.g., a bridge). Finally, the production of the 3D model can start. The 3D production is the most time-consuming and computer-intensive process of the workflow, as shown in Table 8.2.

The computer that was used to process imagery datasets and create 3D models of White Bridge and Benning Bridge has the following system and display device properties:

- Processor: Intel(R) Core (TM) i7-7820HQ CPU @ 2.90GHz (8 CPUs)
- Memory: 64 GB of Random Access Memory (RAM)
- Hard drive: 1 TB Solid State Drive (SSD)
- Graphics card: NVIDIA Quadro M2200.

8.2.1 White Bridge 3D model - Photograph acquisition with a DJI Mavic Mini

The DJI Mavic Mini collected 98 photographs from two manual flight missions performed at White Bridge to create a 3D model. ContextCapture analysed the dataset and used 68 (69%) photographs which formed part of the final 3D model (see Figure 8.7). However, 30 (31%) of the collected photographs were not usable for reconstruction purposes due to improper image composition and insufficient overlapping between the photographs. Chen, Laefer, Byrne & Natanzi (2017) found that the geometric accuracy, data completeness level and point uniformity are significantly degraded by larger shooting angles. ContextCapture requires an angle of less than 15 degrees between different viewpoints of the same part of the bridge for photographs to be used for reconstruction (ContextCapture, 2019).

The extract from the ContextCapture software (see Figure 8.6) shows several photographs and camera angles represented by rectangles and pyramid shapes. The yellow and orange pyramids display the camera positions and orientations with respect to the bridge. The data acquired from the yellow pyramids were usable while the data from the orange pyramids did not meet the acceptable viewpoint angles with respect to the bridge and overlapping requirements between consecutive photographs. It appears that the photographs represented by the orange pyramids were taken at an angle, whereas the RPA pilot thought they were taken perpendicular to the bridge. This may be due to specific limitations in the Mavic Mini and/or user error. Further testing and verifying are required.

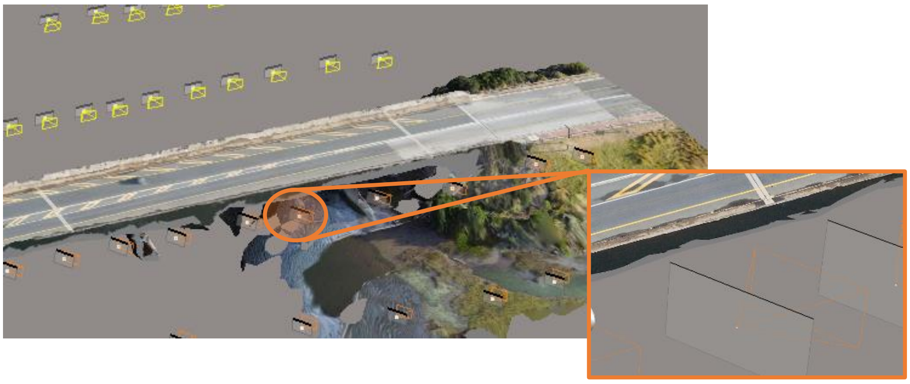


Figure 8.6 Extract from ContextCapture showing usable (yellow pyramid) and unusable (orange pyramid) photographs.

The size of the imagery dataset consisting of 98 photographs is 406 Megabytes (MB), with a total of 882.0 megapixels. The aerotriangulation processing time of the 98 photographs was approximately 4 minutes. The processing time for the creation of the 3D bridge model using 68 photographs was approximately 19 minutes. The imagery dataset properties and processing times of aerotriangulation and 3D modelling are summarised in Table 8.2.

Table 8.2 Comparison of 3D model metrics based on different RPA platforms and flight methods.

RPA Platform	**DJI Mavic Mini**	**DJI Phatom 4 Pro**		
Flight method	Flight method 1	Flight method 2		
Metrics	Free flight (Manual)	Single grid (Autonomous)	Double grid (Autonomous)	Double grid + free flight (Semi-autonomous)
Number of photographs in imagery dataset	98	50	100	225
Imagery dataset size (MB)	406	406	810	1790
Imagery dataset aggregate megapixels	882	998.1	2000	4500
Aerotriangulation processing time (minutes)	4	3	6	13
3D model creation processing time (minutes)	19	27	39	196

The photo acquisition during the manual flight missions, as discussed in Section 7.3.1, produced photographs with varying distances and angles of skew relative to the bridge as well as inconsistent overlapping between consecutive photographs. Nonetheless, ContextCapture was able to reconstruct the photographs to create a 3D model of White Bridge (see Figure 8.7). The deck roadway was considered the only usable rendered bridge component of the 3D White Bridge model to check road marking and extract road widths. The other bridge components were poorly reconstructed and as a result this 3D model was discarded.

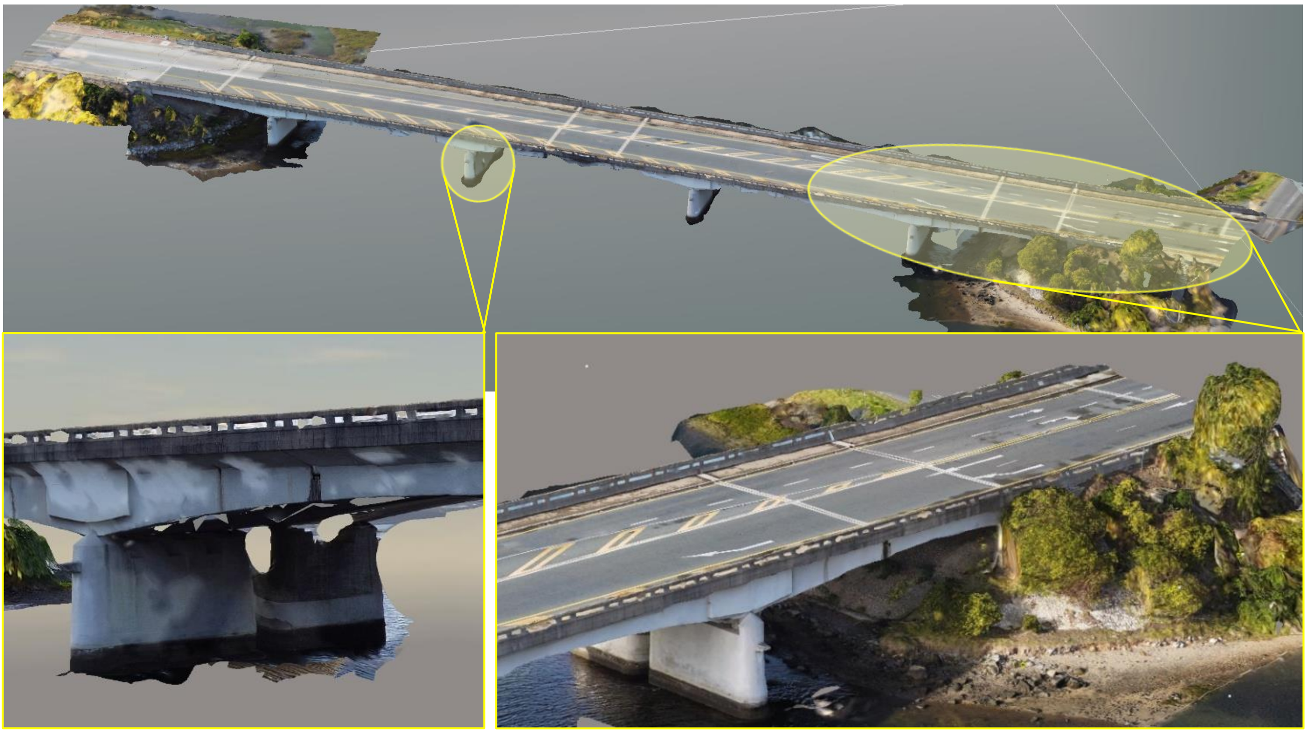


Figure 8.7 White Bridge 3D model.

8.2.2 Benning Bridge 3D models - Photograph acquisition with a DJI Phantom 4 Pro

The DJI Phantom 4 Pro collected a total of 225 photographs from the respective autonomous and semi-autonomous flight missions which were performed at the Benning Bridge site. The photographs were sorted into different imagery datasets for each flight mission. Three 3D bridge models were developed of Benning Bridge using the imagery datasets. Model 1 as shown in Figure 8.8 (a) and Model 2 as shown in Figure 8.8 (b) were developed from photographs collected during the single grid and double grid flights, respectively. Model 3 as shown in Figure 8.8 (c) was developed from photographs that were collected during the double grid flight combined with a free flight mission. A breakdown of the imagery dataset properties, processing times of aerotriangulation and processing times of the 3D modelling for each model are shown in Table 8.2.

Model 1 and Model 2 were reconstructed poorly, with only the bridge roadway and abutments/embankments considered to be usable for inventory acquisition purposes. These models were deemed unusable and discarded. Model 3 was however considered usable for inventory acquisition purposes. The inventory data were manually extracted from Model 3 and used to populate the standard TMH19 inventory information on StrumanBMS. The official 2019 BMS inventory was used to cross-check and verify the accuracy of data obtained from the 3D model.

(a) 3D **Model 1** using photographs obtained during a single grid autonomous flight mission

(b) 3D **Model 2** using photographs obtained during a double grid autonomous flight mission

(c) 3D **Model 3** using photographs obtained during a double grid autonomous flight and free flight

Figure 8.8 3D bridge models developed using photographs obtained from autonomous and free flights with the DJI Phantom 4 Pro.

The inventory information that would typically be collected on site by the technical assistant was successfully extracted from Model 3. In addition, a subset of inventory photographs is shown in Appendix L2 which was extracted from the photorealistic 3D bridge.

8.3 Virtual safety inspection of Benning Bridge

Model 3 was used to perform a virtual safety inspection of Benning Bridge as an alternative approach to human-based inspections to meet the provisions of the CR2014. These regulations only state the purpose and frequency of safety inspections and do not provide guidelines or methodologies on how to meet this requirement. As such, several of the TMH19 inspection items were used as a point of reference for the safety inspection. The following results and findings were derived from the off-site structural condition assessment performed using the 3D model:

i. **Waterways**: Although the water surface of the Steenbras River was not successfully reconstructed, the effect of the waterway on the bridge and surrounding elements could be checked with a specific focus on:
   a. Scour and river movement
   b. Embankment erosion
   c. Build-up of debris.

ii. **Foundations**: Problems in foundations usually arise with unforeseen or excess movements due to failure or settlement of the foundation's founding material. As a result, small movements may sometimes be difficult to detect; however, clear indications of problems that could be observed and monitored using the 3D model were:
   a. The joint detail was clear and therefore sufficient to view unusual or excessive movement at the expansion joints. Checking the joint performance when overlaying future models is recommended
   b. Changes in as-built geometry by overlaying cross sections of the 3D model.

iii. **Substructures:** Concrete elements such as the abutment and piers could be checked for cracking, spalling and general deterioration because of settlement, corrosion of reinforcement and inadequate operation of expansion joints.

iv. **Bearings:** Although enough clearance was available for the RPA to fly underneath the deck and the camera was able to tilt upwards, the bearings were poorly reconstructed in the model. As a result, the condition of the bearings and bearing seatings could not be assessed in terms of their positioning, alignment and signs of cracking.

v. **Bridge decks (excluding the deck soffit):** The deck soffit was poorly rendered and could not be assessed using the 3D model, which could be considered a fatal flaw. The following items were however identified:
   a. Spalling of concrete, specifically at support points in elevation
   b. Cracking
   c. Corrosion of reinforcement
   d. Leakage of water at joints
   e. Deterioration of surfacing on the deck
   f. Accident and bridge impact damage
   g. Alkali aggregate reaction.

vi. **Expansion joints:** Expansion joints are generally considered weak points and the following main defects could be observed:

a. Leakage of water was visible on the model.

vii. **Drainage:** The following main items were assessed:

a. Water stains on concrete members
b. Accumulation of debris.

viii. **Safety features such as balustrades/parapets, guardrails and handrails:** The following main items could be assessed:

a. Mechanical damage due to traffic accidents
b. General deterioration of concrete
c. Theft/vandalism and corrosion of metal parts.

Model 3 was given to an accredited bridge inspector to perform a virtual safety inspection using a draft safety inspection evaluation sheet (Appendix L1). The inspector was able to identify that the structure was in good condition, despite it being difficult to identify small cracks and spalls. It was also mentioned that deck soffit and selected areas of the approach roads were poorly rendered in the 3D model.

The results of the virtual safety inspections were validated against the 2019 principal inspection results (Appendix L3). The accredited bridge inspector was comfortable to render the structure safe for use based on the virtual inspection, but only in conjunction with the findings of the 2019 principal inspection results for Benning bridge. The inspector was however concerned about the following aspects of this approach:

- It may take time for inspectors to learn, effectively execute and be comfortable with using this technology for rendering structures safe for use.
- The 3D model provides more data to evaluate in the office compared to physically completing a similar inspection on site. This approach may therefore be more time consuming.
- Even though the bridge model is three-dimensional, it is presented on a two-dimensional platform such as a desktop/laptop screen. This requires the inspector to zoom in/out and rotate the image to achieve similar views, perspectives and spatial orientation, all of which is time consuming.

Further testing is required on a larger sample size (i.e., more bridges evaluated by several different inspectors) to corroborate the feasibility of virtual safety inspection on a network level.

8.4 Chapter summary

The chapter offers detailed information on using RPAs for bridge inspection activities and includes guidance on how to acquire, process and use the visual data produced during RPA flights on a network level. The collection of inventory data, the development of 3D models and virtual desktop safety inspections are covered in depth for two RPA types at two selected bridge sites.

The aerial images taken by RPAs accelerated and simplified the collection of inventory photographs as required in terms of TMH19 for StrumanBMS. The DJI Mavic Mini and DJI Phantom 4 Pro were able to effectively acquire similar or better-quality inventory photographs at the bridge site than the conventional manual method. Although the Mavic Mini can only be flown manually, the process to collect all the required photographs was faster than the conventional manual method. The DJI Phantom 4 Pro was also flown manually to collect the inventory photographs; however, this RPA type can repeat the same flightpaths, which will result in even faster future photograph acquisitions during bridge inspections.

Additional images were collected and used for the development of 3D bridge models. The models were used for extracting inventory data and conducting virtual safety inspections. The DJI Mavic Mini was not successful in collecting photographs for the creation of detailed 3D models. The 3D models were poorly rendered and not usable for extracting inventory data or conducting virtual desktop safety inspections.

The 3D models created from the imagery of the DJI Phantom 4 Pro were suitable for manually extracting all the standard TMH19 inventory information. These models were further used to conduct a virtual desktop safety inspection in accordance with the provision of the Construction Regulations 2014. As data collection by the DJI Phantom 4 Pro is easily and accurately repeatable at a low cost, imagery can be obtained at regular intervals for tracking changes at bridge sites and the natural environment.

The 3D bridge models of the White and Benning Bridges were visually assessed for completeness through evaluating the quality and detail of several bridge component renders. Each bridge component render was assigned a grading of either usable (✓) or unusable (✗) for inventory acquisition and summarised in Table 8.3. If 75% or more of the bridge component renders were deemed usable, the 3D model was considered a success. If not, the model was discarded.

Table 8.3 Assessment and grading of bridge component renders.

Main bridge component renders	**White Bridge Model 1** **Figures 8.6 & 8.7**	**Benning bridge Model 1** **Figure 8.8 (a)**	**Benning Bridge Model 2** **Figure 8.8 (b)**	**Benning Bridge Model 3** **Figure 8.8 (c)**
Deck roadway	✓	✓	✓	✓
Deck soffit	✗	✗	✗	✗
Balustrades	✗	✗	✗	✓
Piers	✗	✗	✗	✓
Abutments	✗	✗	✗	✓
Embankments	✗	✓	✓	✓
% deemed usable	17%	33%	33%	83%
3D Model usable for inventory acquisition?	No	No	No	Yes

Benning Bridge Model 3 was successfully used to conduct a virtual safety inspection in conjunction with the 2019 principal inspection results and render the structure safe for use.

9 Conclusions

The Department of Transport and Public Works of the Western Cape is accountable for effectively managing its bridges and culverts on a network level. This requires routine principal and safety inspections in accordance with various technical manuals and regulations. To fulfil this role successfully, the Department must ensure that inventory and conditional assessment data of infrastructure are captured, collated and verified. The data support key decision-making processes throughout the structure lifecycle and enable the Department to plan ahead and increase its business efficiency.

Using the conventional human-based bridge inspection methods as outlined in the TMH19, principal inspections on a network level are resource intensive, time consuming, costly, dangerous at times, and may yield subjective results. Furthermore, the Department is unable to meet the safety inspection requirements of the Construction Regulations 2014 due to limited resources, lack of official safety inspection guidelines and the high frequency of these inspections.

To address shortcomings in conventional inspection practices and meet the regulatory safety inspection requirements, off-the-shelf RPA technologies are proposed to obtain inventory data more effectively and to conduct virtual safety inspections.

This chapter presents findings and concluding remarks for the aim and research objectives of this thesis.

9.1 Aspects of conventional human-based visual inspections that were time consuming and/or costly and/or hindered the quality of data

Various aspects of conventional human-based visual inspections that are time consuming and/or costly and/or hindered the quality of data are listed and discussed below. These aspects are a synthesis of the literature review findings, personal observations of actual principal inspections and insights obtained from the interviews with accredited bridge inspectors.

1. Aspects that were considered to be time consuming:

   Capturing and processing of inventory data. A substantial amount of time is required to collect and process inventory data, leading to delays in completing the scope of works. Transferring handwritten field inspection notes to the bridge management system software causes further delays.

   Gaining physical access to the structure and surroundings. At several bridge sites, inspectors and technical assistants had to climb over barbed wire fencing and make their way through and around overgrown vegetation in waterways at the inlets/outlets of structures and climb up/down steep embankments. Furthermore, to safely navigate high traffic volumes and high-speed traffic along freeways and dual carriageways extended the fieldwork times. Inspectors had to make certain adjustments to obtain the required inventory photographs at these sites. Walking to and finding the correct position to capture the extreme photographs, i.e., elevations of large structures, was time consuming.

   Training of staff. From the types and numbers of errors found in the principal inspection data analyses, it was evident that external service providers did limited or no training and calibration. The training of bridge inspection teams should receive priority if additional technology and/or approaches are developed, introduced or required by the WCG.

2. Aspects that were costly:

   The cost of bridge inspections is directly related to the time it takes to complete the inspections and to submit the data to the Department, i.e., the more time spent on site and in the office processing the data, the higher the costs to the external service providers and the Department. Therefore, all the aspects that were considered time consuming were also considered costly.

3. Aspects that affected the quality of data:

   Lack of the prescribed inspection equipment on site that resulted in poor quality photographs and gaps in the data. Not all of the inspection teams made use of binoculars, flashlights, the correct prescribed digital cameras, and/or ladders to access out-of-reach or out-of-sight areas such as the bridge bearings or shaded areas of a bridge soffit. None of the inspection teams made use of an RPA.

   Contaminated rivers and security risks to the inspection teams resulted in structures not being inspected or partially inspected, hindering network level analysis of the provincial bridge stock due to gaps in the data. Contaminated water bodies were not accessed by inspectors, resulting in elements of a structure not being inspected. In addition, safety concerns for inspectors in high crime/violence areas were noted. This was concerning given the perceived high value of equipment that inspectors are mandated to use.

   Human errors in the data. Discrepancies in the data were categorised as mistakes and/or accidental errors made by the inspection teams. Mistakes were made due to the inspection teams' carelessness or inexperience while undertaking visual inspections. Errors were made due to incorrectly capturing and recording of measurements and populating erroneous data on StrumanBMS.

9.2 The feasibility of RPAs to obtain inventory data on a network level

Two alternative approaches for obtaining inventory data during principal bridge inspections were evaluated by using off-the-shelf RPAs to streamline the current methods.

a) A low-cost RPA was employed as a supplementary tool, collecting inventory photographs as described in the TMH19 during principal bridge inspections. An RPA is eminently suitable for this purpose, reducing time spent on site to capture inventory photographs of large bridges and to avoid obstructions such as dense vegetation, fencing, steep embankments and/or flowing rivers. The approach is easy to implement, the additional equipment required is minimal, and it is inexpensive.

   Despite these advantages, the approach is not feasible if it cannot be executed by the bridge inspection team. The additional cost to employ a remote pilot and flight crew for network level inspections may possibly not be recovered through the time and cost saved at selected bridge sites using an RPA.

b) An optimal number of photographs of a structure and its surroundings were collected with a mid-range RPA. These photographs included the minimum inventory views as described in the TMH19. Using all the collected photographs, a photo-realistic 3D digital model is created and then used as a reference model to manually extract inventory data. The 3D model provides a fast and easy-to-navigate visual and information retrieval platform.

   The extracted data are directly populated on StrumanBMS, therefore eliminating the need to transfer data from paper notes to the digital platform. Inspectors also use the 3D model to review numerous inspection items from high-quality inventory photographs while having a holistic view of the structure and its surroundings. Images of the approach roads, watercourses and features underneath the structures can be viewed from multiple angles and used for post-inspection discussion purposes, planning and high-level quantitative assessments.

   Although utilising off-the-shelf RPAs and manually extracting data from digital 3D models do not completely replicate or automate the principal bridge inspection process, the proposed approach is advantageous and feasible on a network level if a Remote Operator Certificate (ROC) for the Department is in place. The 3D models are easy to develop and use, suitable for the Department's in-house technical staff and implementable on a network level. Technical staff can quickly and accurately extract useful inventory data without the need for automated, complex element identification, damage detection and algorithm mapping. Site notes and tedious measurements of structure dimensions by laser or taping is avoided. It mitigates human error by eliminating the need to recapture inventory data and reduces time spent on site. The approach yields safe, cost-effective, high quality and consistent structure inventory data by using low-cost, off-the-shelf and easy-to-fly RPAs.

Both of these approaches will only be feasible if the Department is a holder or member of a ROC and allows external service providers to operate RPAs under their ROC. A valid ROC will allow the Department to employ and utilise in-house staff and bridge inspection team members who hold a Remote Pilot Licence (RPL) to perform these bridge inspection activities within the standard operating conditions, as governed by SACAA. This will provide and facilitate significant growth and learning opportunities for the bridge inspection and asset management industry.

9.3 The feasibility of RPAs for off-site virtual safety inspections on a network level

An investigation was conducted into the use of off-the-shelf RPAs and photogrammetric technology to create digital photo-realistic 3D models for off-site virtual safety inspections. Several models were developed using different flight parameters to determine the minimum criteria needed to create a usable 3D model for a virtual safety inspection. An off-site, computer-based visual evaluation of the structure was performed to determine whether the structure was fit for its intended design purpose and safe for continued use. Due to the lack of official guidelines and methods in the Construction Regulations 2014 to perform safety inspections, several of the TMH19 inspection items were used as a point of reference for evaluation purposes and uniformity. A draft safety inspection evaluation sheet was developed and populated by an accredited bridge inspector using the photo-realistic 3D model (see Appendix L3).

It was shown that the conditional information could be manually extracted quickly and with little effort, and that the information was sufficient to be used for a high-level visual assessment. The virtual inspection eliminated the need for field notes, mitigated gross mistakes and it unlikely that any detail of importance was omitted. However, assigning condition assessment ratings to the observed defects in terms of degree, extent, relevance and urgency proved to be challenging. The deck soffit, deck seating area and bearings were however poorly rendered. It was not possible to evaluate the poorly rendered structural elements and this introduced doubt regarding the approach. Additional photographs using more sophisticated RPAs or in combination with ground-based photography are required to create digital 3D models that will show all the structural elements for evaluation purposes.

As this approach is untested in South Africa and to mitigate any risks to the Department, an off-site virtual safety inspection may therefore be limited to structures in a good or very good condition only, i.e., a structure with a Priority Condition Index (PCI) of 70 points or higher (Appendix I). The virtual safety inspection should be done in conjunction with the results of the previous principal inspection results. The outcomes of the safety inspections must be validated on site until the process is more refined and accepted as an official method to conduct safety inspections by the Department.

10 Recommendations

This thesis investigated the feasibility of RPA technology for bridge inspection activities on a network level in the Western Cape. The following recommendations are made to address shortcomings in current technical manuals and regulatory provisions and increase business efficiencies at the DTPW. There are also recommendations for future studies based on the findings and conclusions of this thesis.

10.1 Recommendations to address shortcomings in regulatory provisions and in current technical manuals

The CR2014 contains no specific requirements for collecting and assessing visual data to render a structure safe for use. The TMH19 provides details on human-based inspections but has yet to include information on the use of RPAs. The incorporation of RPA technology into these regulations and technical manuals is therefore recommended.

In this research, it was determined that RPAs could capture a full digital record of the bridge and its surroundings in the form of a photo-realistic 3D model. The 3D model was used to perform a virtual safety inspection in combination with an adapted TMH19 Principal Inspection Sheet. Due to a lack of official guidelines, the Safety Inspection Sheet was specifically developed for competent persons to quickly assess and declare bridges safe for use or not. To reduce the level of risk to the public and the competent person, the virtual safety inspections should only be conducted on structures in a very good or good condition. There are however several important aspects that require further investigation, and the following is recommended:

a) An evaluation of the effectiveness of the Safety Inspection Evaluation Sheet through a comparison study. Several bridges of varying condition (very good, good, poor, very poor) across the road network should be identified. These bridges should be inspected by both conventional human-based methods and virtual desktop evaluations using photo-realistic 3D models. The results must be compared to determine discrepancies and consistencies in the assessment outcomes of the two methods.
b) Qualitative research and experimental testing should be conducted to determine whether competent persons are able and comfortable to render a structure safe for continued use following a virtual desktop assessment. A detailed list of parameters and aspects should be identified that could influence a person’s ability to successfully complete a Safety Inspection Sheet using a photo-realistic 3D model.

10.2 Recommendations for the Department of Transport and Public Works of the Western Cape Government

The following recommendations are made for the Department of Transport and Public Works of the Western Cape and other provinces in SA.

10.2.1 Separate inventory photograph/data acquisition from network level principal inspections

Separating inventory acquisition from principal bridge inspections on a network level should be investigated by means of a pilot study during the next round of principal inspections. The acquisition and processing of inventory data are considered some of the most time-consuming tasks during principal inspections performed by external service providers for the Department. This mandatory process is costly for the Department and frustrating to the inspection teams. Therefore, a more productive approach using RPA technology and a combination of staff from the Department and external service providers should be explored.

Staff from the Department should comprise technical staff who are eligible to obtain a Remote Pilot Licence (multi-rotor) for corporate use. The in-house staff should be identified, receive training and obtain a valid remote pilot licence prior to the next round of inspections. Providing this type of training opportunity enables staff to upskill and enhance their technical capabilities while the Department explores new ways to improve service delivery to the public. In addition, entry level staff from the Department will have an opportunity to learn practical inspection skills and competencies from accredited inspectors during principal inspections.

Removing inventory acquisition from principal inspections could also be advantageous to external service providers performing the bridge inspections, as they can focus solely on performing condition assessments. External service providers are also exposed to new technologies and methods at no additional cost to them. It is therefore recommended that a relationship with accredited inspectors be developed, as it could lead to quicker industry adoption of RPAs to form part of the bridge inspection toolkit.

10.2.2 Development of an automated inventory data platform

It is recommended that an automated inventory data platform based on digital 3D models be developed. The aim is to create an intuitive platform to collect, verify, convert and produce validated inventory data outputs.

a) **Collect** data by using off-the-shelf RPAs and a diverse range of payloads, including dual cameras, infrared cameras and lidar scanners.
b) **Verify** data by developing refined processes and algorithms to automatically identify the structure type, class, subclass, and different structural elements from a diverse dataset.
c) **Convert** and adapt the verified data by developing accurate digital 3D models to automatically extract data in accordance with the user requirements and technical manuals. The most effective digital 3D model format should also be explored.
d) **Deliver** validated inventory data outputs in a format which can be used to automatically populate the StrumanBMS inventory module and adapted for use on similar infrastructure management software.

The platform should be integrated with building information modelling (BIM). This will be particularly useful to produce record data and drawings for older structures on the provincial road network that lack as-built drawings and/or record data.

10.2.3 Develop a Strategic Inspection Plan for general authorisation from SACAA to conduct RPA flights at provincial bridge sites for inspection purposes

The purpose of a Strategic Inspection Plan (SIP) is to define the parameters for bridge inspection activities in terms of the TMH19 and the Construction Regulations 2014. It is recommended that the SIP provides guidelines which set out steps and actions at each bridge site. This is to ensure that RPA flights are within the provisions of the National Legal and Local Regulatory frameworks. The SIP will promote sustainable implementation and management of RPA technology on a provincial network level, whilst avoiding and/or mitigating any public safety and infrastructure damage during operations.

To ensure document brevity and to mitigate misuse, it is recommended that SIP only applies to inspection activities at provincial bridge sites of the Department of Transport and Public Works of the Western Cape Government and does not apply to any activities or sites which fall outside the recorded locations. RPA operations on any other infrastructure must be applied for and authorised prior to commencement in terms of Part 101 of the Civil Aviation Regulations, 2011 as amended by GNR 40376 of 28 October 2016 and GNR 432 of 19 May 2017 with effect from 21 June 2017.

Similar strategic initiatives have been successfully achieved in countries such as the United States of America. Their Federal Aviation Administration has approved a first responder tactical Beyond Visual Line of Site (B-VLOS) waiver to support public RPA operators to conduct B-VLOS operations for bridge inspections amongst other activities (FAA, 2020).

10.3 Recommendations for future studies

As in several engineering fields, the increasing use of and interest in RPA technology have challenged manual human-based methods for collecting data and assessing infrastructure. With the current high demand and use of RPAs, manufacturers have increased the performance while the cost and size of this technology has decreased. An inspection team can now use a pocket-sized RPA to collect photographs faster and with the same or better quality than a digital handheld camera. Furthermore, computers, software and cloud-based processing have increased in capacity and performance, and as a result provide many post-processing options.

Further investigations into RPA technology on a network level would continue to promote more effective approaches to collecting inventory data and performing safety inspections by leveraging the advancements in visual-based systems, geospatial data, optical sensors and machine learning to automate data extraction and processing. In addition, the following proposals are made for further research:

a) During the interview process it was noted that the inventory requirements for network level principal inspections were disproportionate (with regard to time) to the condition assessment requirements. Automation processes should therefore be investigated for bulk processing of large photograph datasets to automatically re-label, group, re-size and file the inventory photographs using geospatial and orientation data with reference to each bridge.
b) Automatically grouping and filing photographs based on the geospatial data will simplify and reduce time to develop photorealistic 3D models in Bentley ContextCapture. However, due to the processing power required to create photo-realistic models, cloud-based processing should be investigated and compared to using a personal computer.
c) In addition to Point b above, the use of point cloud models should be considered as opposed to photo-realistic models for inventory data extraction. Point cloud models require less storage size than photo-realistic models and would be advantageous for use on a network level to reduce large datasets.
d) To ensure that the information remains accessible in the future as technology advances, the format in which digital 3D models are stored and archived and how this is managed should be investigated.

e) More research is required to create autonomous RPA flights that include elevation changes during the flight mission, thereby eliminating the need for free flight. Completely autonomous flights around bridge sites will support more consistent and repeatable data collection and ensure optimal overlapping of photographs to create more accurate digital 3D models.

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Appendices

Appendix A

Consent form for interviews

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WRITTEN CONSENT TO PARTICIPATE IN RESEARCH

TITLE OF RESEARCH PROJECT:	An investigation into the feasibility of using commercially available Unmanned Aerial Vehicles for bridge inspection activities for the Department of Transport and Public Works of the Western Cape Government
REFERENCE NUMBER:	ING-2019-11584
PRINCIPAL INVESTIGATOR:	Johannes Henoch Neethling
ADDRESS:	Faculty of Engineering (Banghoek Road, Stellenbosch, 7600)
CONTACT NUMBER:	073 952 9707
E-MAIL:	Johannes.Neethling2@westerncape.gov.za

Dear Participant

Kindly note that I am a MEng student at the Department of Civil Engineering at Stellenbosch University, and I would like to invite you to participate in a research project entitled an investigation into the feasibility of using commercially available small Unmanned Aerial Vehicles for bridge inspection activities for the Department of Transport and Public Works of the Western Cape Government.

Please take some time to read the information presented here, which will explain the details of this project and contact me if you require further explanation or clarification of any aspect of the study. This study has been approved by the Research Ethics Committee (REC) at Stellenbosch University and will be conducted according to accepted and applicable national and international ethical guidelines and principles.

1. INTRODUCTION:

This research project covers the investigation into the feasibility of using commercially available, off-the-shelf, Unmanned Aerial Vehicles (UAV's) to increase the efficiency of visual inspection activities for bridges and major culverts for the Department of Transport and Public Works (DTPW) of the Western Cape Government (WCG).

The WCG has approximately 3000 bridges and major culverts that require visual inspection to be performed to ensure bridges and culverts are, and remain, fit for its intended purpose and safe for continued use.

A need therefore exists to develop efficient, safe and cost-effective methods to obtain current inventory and condition data whilst adhering to the required regulations. This will assist authorities to have an updated BMS and make critical and technical decisions with circumspection. Due to the rapid advancement of commercially available UAV's, an alternative and innovative approach is envisaged for future bridge inspection activities.

2. CONFIDENTIALITY:

Your personal and company information will not be recorded as part of this research and sources of this data will be cited as anonymous. Access to all electronic data will be password protected. The laptop that I use is not a shared laptop i.e. I am the only user. The laptop is either with me or at home in a locked bedroom. This will ensure the confidentiality of the collected data. The information gathered during this interview will only be used for research purposes, specifically related to my thesis. The participant will not be requested to provide any personal information during the interview, which can identify him/her as an individual. The only form of personal data required is the participant's job title and area of expertise. **The name of the participant and the name of the company where the participant works will not be disclosed**. My research report will not contain any direct quotes or links to any personal identifiers. Any form of correspondence between the participant and the principal investigator will be kept confidential, and only the principal investigator and his supervisor (Chris Jurgens) will have access to this information. The responses obtained during this interview will be assigned a unique reference number, which will be used to identify data in the thesis itself.

3. PURPOSE:

The overarching goal of using small Unmanned Aerial Vehicles (UAV's) for bridge inspection activities is to decrease the time and cost spent on overall visual assessment processes in order to address mandatory inspection backlogs for legal compliance. Based on this goal, the following objectives were identified:

- Identify aspects in conventional visual assessments and TMH19 methods that are time-consuming, costly and/or hinder the quality of data.
- Evaluate how UAV's can be used to improve the effectiveness of visual assessments.
- Develop a method to pre-determine flightpaths for a UAV to capture inventory photographs in a semi-autonomous manner.
- Make recommendations on the feasibility of using UAV's as part of visual inspections for WCG DTPW and potentially for other national, provincial and municipal authorities.

4. PROCEDURES:

Accredited inspectors (professional structural engineers) will be observed and timed during routine bridge and major culvert inspections. Inspectors will be interviewed to identify ways and means of improving existing inspection methods by using UAV's. South African Remote Pilot Licence (RPL) holders will also be interviewed to assess the current UAV market and demand in South Africa and specifically in the Western Cape.

5. TIME:

The length of time for the interview will be approximately between 15 and 60 minutes.

6. RISKS:

I don't foresee any potential risks, discomforts, or inconveniences about the participant partaking in the interview.

7. BENEFITS:

The research aims to provide, amongst other things a potential better, safer and more cost-effective method of conducting bridge and major culvert inspections in the future. This is beneficial to both the road authority and inspectors doing the work.

8. PARTICIPATION & WITHDRAWAL:

Should you wish to withdraw at any time during or after the interview, the hard copy of this document will be destroyed, and you will be withdrawn from the interview. Any responses that have been provided by you will remain anonymous. I will also destroy any written notes or electronic copies related to your responses.

9. RECORDINGS:

No voice or video recordings of the interview will be made.

10. DATA STORAGE:

All electronic data will be stored on a password-protected laptop and on my password-protected OneDrive account. The laptop is stored in my lockable bedroom at my apartment. All paper data will be stored in a file planner in my lockable bedroom in my apartment. Once data capturing is complete all paper will be shredded. Data will be backed up weekly on a password-protected external storage device which will be locked away in my room at my apartment. The data is also uploaded continuously to a password-protected OneDrive account. I am the only person that will have access to the data.

If you have any questions or concerns about this research project, please feel free to contact me (Johannes Neethling) or my study leader (Chris Jurgens). Our contact details are as follows:

Johannes Neethling:	**E** Johannes.Neethling2@westerncape.gov.za	**T** 021 483 0537 **C** 073 952 9707
Chris Jurgens:	**E** cj@sun.ac.za	**T** 021 808 4078 **C** 074 130 8243

RIGHTS OF RESEARCH PARTICIPANTS: You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché (mfouche@sun.ac.za / 021 808 4622) at the Division for Research Development. You have the right to receive a copy of this Consent form.

If you are willing to participate in this research project, please sign the Declaration of Consent below and hand it the signed form back to me.

DECLARATION BY THE PARTICIPANT

As the **participant** I hereby declare that:

- I have read the above information and it is written in a language with which I am fluent and comfortable.
- I have had a chance to ask questions and all my questions have been adequately answered.
- I understand that taking part in this study is voluntary and I have not been pressurised to take part.
- I may choose to leave the study at any time and will not be penalised or prejudiced in any way.
- If the principal investigator feels that it is in my best interest, or if I do not follow the study plan as agreed to, then I may be asked to leave the study before it has finished.
- All issues related to privacy, and the confidentiality and use of the information I provide, have been explained to my satisfaction.

By signing below, I ______________________________ *(name of participant)* agree to take part in this research study, as conducted by Johannes Neethling.

_______________________________________ _____________________________

Signed at *(place)* **Date**

____

Signature of Participant

DECLARATION BY THE PRINCIPAL INVESTIGATOR

As the **principal investigator** I hereby declare that the information contained in this document has been thoroughly explained to the participant. I also declare that the participant has been encouraged (and has been given ample time) to ask any questions. In addition, I would like to select the following option:

	The conversation with the participant was conducted in a language in which the participant is fluent.
	The conversation with the participant was conducted with the assistance of a translator, and this "Consent Form" is available to the participant in a language in which the participant is fluent.

Cape Town

_______________________________________ _____________________________

Signed at *(place)* **Date**

____

Signature of Principal Investigator

Appendix B

Interview protocol

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INTERVIEWS WITH INDUSTRY PROFESSIONALS AND/OR SPECIALISTS

TITLE OF RESEARCH PROJECT:	An investigation into the feasibility of using commercially available Unmanned Aerial Vehicles for bridge inspection activities for the Department of Transport and Public Works of the Western Cape Government
REFERENCE NUMBER:	ING-2019-11584
PRINCIPAL INVESTIGATOR:	Johannes Henoch Neethling
ADDRESS:	Faculty of Engineering (Banghoek Road, Stellenbosch, 7600)
CONTACT NUMBER:	073 952 9707
E-MAIL:	Johannes.Neethling2@westerncape.gov.za

1. INTERVIEW PROTOCOL

The interviews will be conducted on a one-on-one basis at a place and at a time of the participant's choosing. It is envisaged that most participants will be interviewed at their own companies' premises. The interviews follow predetermined questions. Record keeping will be by means of notetaking only. Interviews will not be recorded by means of an electronic device/apparatus.

2. CONFIDENTIALITY

Your personal and company information will not be recorded as part of this research and sources of this will be cited as anonymous. This discussion will not be recorded. Record keeping will be by means of notetaking only. All the interview notes will be emailed to you for validation and approval. All electronic data will be stored on a password-protected laptop and on my password-protected OneDrive account. The laptop is stored in my lockable bedroom at my apartment. All paper data will be stored in a file planner in my lockable bedroom in my apartment. Once data capturing is complete all paper will be shredded. Data will be backed up weekly on a password-protected external storage device which will be locked away in my room at my apartment. The data is also uploaded continuously to my password-protected OneDrive account. I am the only person that will have access to the data.

If you have any questions or concerns about this research project, please feel free to contact me (Johannes Neethling) or my study leader (Chris Jurgens). Our contact details are as follows:

Johannes Neethling: **E** Johannes.Neethling2@westerncape.gov.za **T** 021 483 0537 **C** 073 952 9707

Chris Jurgens: **E** cj@sun.ac.za **T** 021 808 4078 **C** 074 130 8243

3. SCRIPT AND QUESTIONS

Dear Participant

I currently work as a Structural Engineer in the Road Network Management Branch of the Department of Transport and Public Works of the Western Cape Government. I am also a part-time MEng student at the Department of Civil Engineering at Stellenbosch University. I would like to invite you to participate in a research project entitled "An investigation into the feasibility of using commercially available Unmanned Aerial Vehicles for bridge inspection activities for the Department of Transport and Public Works of the Western Cape Government". I am conducting my research under the supervision of Mr. Chris Jurgens.

You have been invited to participate in this interview because you meet one or both of the following criteria:

a. You are a COTO/SANRAL accredited senior bridge, bridge or culvert inspector; and/or
b. You are an Unmanned Aerial Vehicles (UAV's) pilot with a South African Remote Pilot Licence (RPL).

Today's discussion has reference to my research of using Unmanned Aerial Vehicles (UAV's) for bridge inspection activities to decrease the time and cost spent on overall visual assessment processes and to address mandatory inspection backlogs for legal compliance. Based on this goal, I identified the following objectives:

- Find aspects in conventional visual assessments and TMH19 methods that are time-consuming, costly and/or hinder the quality of data.
- Evaluate how UAV's can be used to improve the effectiveness of visual assessments.
- Develop a method to pre-determine flightpaths for an UAV to capture inventory photographs in a semi-autonomous manner.
- Make recommendations on the feasibility of using UAVs as part of visual inspections for WCG DTPW and potentially for other national, provincial and municipal authorities.

Should you agree to participate in this interview, kindly allow me to ask you the following questions:

Questions relevant to COTO/SANRAL accredited inspectors (senior bridge/bridge/culvert)

i. Are you a senior bridge or bridge or culvert inspector?
ii. In which of the following age ranges do you fall: 25-30; 31-35; 36-40; 41-45; 46-50; 51-55; 56-60; 61-65; 66-70; 71-75?
iii. In your experience, what aspects during bridge or major culvert inspections (following TMH19 methods) did you consider as being time-consuming, costly and/or hinder the quality of data?
iv. With reference to your answers to the previous question and in your own opinion, what technology is currently available to reduce inspection times, reduce the cost of inspections and increase the quality of data obtained during inspections?
v. In your opinion, what are the most time-consuming tasks/processes of bridge inspections during physical inspections on-site and during the post-processing of the data obtained during inspections?
vi. When conducting principal inspection per TMH19, the inspection team is required to capture inventory photos for each structure. In your experience, are capturing inventory photos during principal inspections a time-consuming process? In your opinion, would the total duration spent at each structure be reduced if the capturing of inventory photos were not required? If 'yes', please explain how much time could be saved during inspections. If 'no', why not?
vii. Have you made use of UAV's for bridge/ culvert inspections? If 'yes', please share your experience. If 'no', why not?
viii. Do you know of inspectors, clients and/or firms that have made use of UAVs for bridge/culvert inspections? If 'yes', please elaborate on their experience.
ix. What is your opinion about using UAV's for bridge/culvert inspections?
x. How do you foresee bridge/culvert inspection happening in the future i.e 15 years from today?
xi. What is your understanding of the term "autonomous bridge/culvert inspections using UAV's"?
xii. Did you think that bridge/culvert inspections can be conducted semi or completely autonomously? If 'yes', what would your role be as the inspector? If 'no', why not?
xiii. In your opinion, how can the client assist bridge inspectors to improve the efficiency of bridge inspections?

Questions relevant to UAV pilots with a South African RPL

i. How long did it take to obtain your South African RPL?
ii. In which of the following age ranges do you fall: 25-30; 31-35; 36-40; 41-45; 46-50; 51-55; 56-60; 61-65; 66-70; 71-75?
iii. How many years/months experience do you have post obtaining your RPL?
iv. What are the main industry fields (e.g. filming, agriculture, social works, mining, civil engineering etc.) where you have performed your services as an UAV pilot?
v. Do you have any experience in the design and/or construction and/or inspection of bridges and/or culverts?
vi. Have you ever used an UAV to assist an accredited inspector to inspect bridges/culverts? If 'yes', please share your experience. If 'no', why not?
vii. What is your opinion about using UAV's for bridge/culvert inspections?
viii. What would a typical cost breakdown be if your services were requested to assist in bridge inspections?
ix. How long do you think it would take to inspect a bridge?
x. What software do you use for post-processing of captured data?
xi. How do you foresee bridge/culvert inspections happening in the future i.e. 15 years from today?
xii. What is your understanding of the term "autonomous bridge/culvert inspections using UAV's"?
xiii. Did you think that bridge/culvert inspections can be conducted semi or completely autonomously? If 'yes', what would your role be as an UAV pilot? If 'no', why not?

Thank you in advance for your assistance in this regard.

Appendix C

C1: Principal inspection observation sheet

C2: Observed inspection methods

C1: Principal inspection observation sheet

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INTERVIEWS WITH INDUSTRY PROFESSIONALS AND/OR SPECIALISTS

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REFERENCE NUMBER:	ING-2019-11584
PRINCIPAL INVESTIGATOR:	Johannes Henoch Neethling
ADDRESS:	Faculty of Engineering (Banghoek Road, Stellenbosch, 7600)
CONTACT NUMBER:	073 952 9707
E-MAIL:	Johannes.Neethling2@westerncape.gov.za

OBSERVATION PROTOCOL

The observations will be conducted by myself in the field where inspections are taking place on the Provincial Road Network of the Western Cape. The notes taken during the observations will be in-line with the observation sheet and field notes outline below. Record keeping will be by means of notetaking, sketches and photographs. I will not participate in any assessment activities. I will however take time measurements to calculate the duration of bridge inspection activities.

1. SCRIPT AND OBSERVATION SHEET WITH FIELD NOTES

Dear Participant

I currently work as a Structural Engineer in the Road Network Management Branch of the Department of Transport and Public Works of the Western Cape Government. I am also a part-time MEng student at the Department of Civil Engineering at Stellenbosch University. I would like to invite you to participate in a research project entitled "An investigation into the feasibility of using commercially available Unmanned Aerial Vehicles for bridge inspection activities for the Department of Transport and Public Works of the Western Cape Government". I am conducting my research under the supervision of Mr. Chris Jurgens.

Today's observation has reference to my research of using Unmanned Aerial Vehicles (UAV's) for bridge inspection activities to decrease the time and cost spent on overall visual assessment processes and to address mandatory inspection backlogs for legal compliance. Based on this goal, I identified the following objectives:

- Find facets in conventional visual assessments and TMH19 methods that are time-consuming, costly and/or hinder the quality of data.

- Evaluate how UAV's can be used to improve the effectiveness of visual assessments.
- Develop a method to pre-determine flightpaths for an UAV to capture inventory photographs in a semi-autonomous manner.
- Make recommendations on the feasibility of using UAVs as part of visual inspections for WCG DTPW and potentially for other national, provincial and municipal authorities.

Should you agree that I observe you while you conduct the visual assessment, kindly allow me to make notes and take photographs during your inspection activity. My notes will have reference to the following items in the observation sheet:

Date and time:	
Location:	
Weather:	
Structure type:	
Structure No:	
Type of inspector:	Senior Bridge ◯ Bridge ◯ Culvert ◯ Male ◯ Female ◯ Age:
Are the inspector making use of UAV's?	Yes ◯ No ◯
Description of site:	Easy/difficult to access structure: Safe/Unsafe area: General: Photograph number(s):
Inventory data collection in the field	Method of obtaining information: Start time: End time: Challenges: General remarks:
Condition assessment of structure:	Method of obtaining information: Start time: End time: Challenges: General remarks:

Total duration at bridge:	Preparation time before inspection commence: Total duration of inspection: Duration from when inspector arrives on site until inspector leaves the site: General remarks: Length of observation:
Describe the inspector's method/process of conducting the visual assessment:	
Describe activities that seem time-consuming:	
Summary:	

2. PARTICIPATION & WITHDRAWAL:

Should you wish to withdraw at any time during or after the observation, the hard copy of this document will be destroyed, and you will be withdrawn from the survey. Any notes and photographs that have been taken will be disregarded and destroyed. Notes and photographs of the observation will not be incorporated into my research and I will also destroy any written notes or electronic copies related to this observation.

3. CONFIDENTIALITY

No names of participants will be recorded or added to the observation sheet of the study. Record keeping will be by means of notetaking and photographs only. All the observation notes and photographs will be emailed to you for validation and approval for use in the study. All electronic data will be stored on a password-protected laptop and on my password-protected OneDrive account. The laptop is stored in my lockable bedroom at my apartment. All paper data will be stored in a file planner in my lockable bedroom in my apartment. Once data capturing is complete all paper will be shredded. Data will be backed up weekly on a password-protected external storage device which will be locked away in my room at my apartment. The data is also uploaded continuously to my password-protected OneDrive account. I am the only person that will have access to the data.

If you have any questions or concerns about this research project, please feel free to contact me (Johannes Neethling) or my study leader (Chris Jurgens). Our contact details are as follows:

Johannes Neethling:	**E** Johannes.Neethling2@westerncape.gov.za	**T** 021 483 0537 **C** 073 952 9707
Chris Jurgens:	**E** cj@sun.ac.za	**T** 021 808 4078 **C** 074 130 8243

Thank you in advance for your assistance in this regard

C2: Observed inspection methods

Inspection method 1

1. The technical assistant compiled an inspection file at the office with all the available data of each structure and its location for each day prior to going to site.
2. The technical assistant pre-populates selected inventory data on the printed sheets such as the location description, relevant district roads engineer, region, road name and number, etc.
3. On-site, the technical assistant captured the inventory photographs, sketch the structure and surroundings, took all the measurements with the measuring wheel/tape/laser, and populated the pre-printed inventory sheets on-site.
4. On-site, the accredited inspector manually identified defects, captured the condition assessment photographs, and assigned ratings to defects on printed condition assessment sheets.
5. Steps 3 & 4 were completed simultaneously by the inspection team as they had two cameras at their disposal.

Inspection method 2

1. The technical assistant compiled an inspection file at the office with all the available data of each structure and its location for each day prior to going to site.
2. The technical assistant pre-populates selected inventory data on the printed sheets such as the location description, relevant district roads engineer, region, road name and number, etc.
3. On-site, the accredited inspector captured the inventory photographs and identified defects, captured the condition assessment photographs, assigned ratings to all the defects on the printed inspection sheets, and sketch the structure and surroundings.
4. The technical assistant took and measurements with the measuring wheel/tape/laser and populated the printed inventory sheets on-site. The technical assistant obtained the inventory photographs numbers verbally from the inspector.
5. Only the inspector had a camera and took all the photographs.

Inspection method 3

1. The technical assistant compiled an inspection file printed inventory and inspections sheets for each day prior to going to site. The inspection sheets were not pre-populated with any available information.
2. On-site, both the accredited inspector and technical assistant captured photographs of the inventory items and defects.
3. The technical assistant took all the measurements with the measuring wheel/tape/laser and populated the printed inventory sheets on-site.
4. After the site inspections were completed, the inspector collated and sorted all the photographs between inventory and conditional assessment data. The inspector then used the photographs and his/her personal recollection as reference to assign defect ratings and complete in the printed inspection sheets.
5. Only the inspector had a camera and took all the photographs. It appeared that the inspection team wanted to complete the on-site inspections as fast as possible and relied heavily on post-processing of inspection data (measurement, photographs, field notes, etc.) at the office.

Appendix D

TMH19 inventory view descriptions (relevant section extracted from the TMH19)

3.8 Required Inventory Photos

In order to ensure consistency of photos, a defined set of inventory photos is required. These photos must be uniquely numbered and it is recommended that all photos be geo-tagged.

3.8.1 Bridge (General; Arch; and Cable)

View 1: Bridge in elevation (must show total length of bridge, full pier heights and abutments. If necessary several photos can be taken and combined electronically.

View 2: Bridge in elevation from opposite side.

View 3: Bridge from upper approach (looking along centre line of road or as close as possible to centre line).

View 4: Bridge from upper approach (opposite end).

View 5: View taken from the top of the bridge of feature crossed (road, rail or upstream river view)

View 6: View taken from the top of the bridge of feature crossed (road, rail or downstream river view).

View 7: Deck edge to show profile of deck cantilever soffit.

View 8: Opposite deck edge to show profile of deck cantilever soffit.

View 9: Underside of deck (photo of each type if different deck types).

View 10: Typical pier (photo of each type if different pier types).

View 11: Typical abutment (photo of each type if different abutment types).

View 12: Bridge number as seen from main route on which bridge is defined.

View 13: Other bridge number adjacent to other road or rail.

View 14: Typical parapet elevation.

View 15: Typical roadway joint.

View 16: Any other salient feature

3.8.2 Bridge (Cellular)

View 1: Bridge inlet in elevation (show total number of cells);

View 2: Bridge outlet in elevation (show total number of cells and apron slab);

View 3: Bridge from upper approach (in direction of increasing chainage);

View 4: Bridge from opposite end of approach (in direction of decreasing chainage).

View 5: View taken from the top of fill of feature crossed (road or upstream river view);

View 6: View taken from the top of fill of feature crossed (road or downstream river view);

View 7: View of inside of bridge barrel showing roof walls & floor.

View 8: Bridge number.

View 9: Any other salient feature.

3.8.3 Culvert (Major)

View 1: Culvert inlet in elevation (show total number of cells);

View 2: Culvert outlet in elevation (show total number of cells and apron slab);

Appendix E

WCG scope of works structure size category definitions

1 General requirements

1.1 Definitions

"**Certified Bridge Inspector**" means a person issued a certificate by COTO/SANRAL stating that he is a certified bridge Inspector. A Certified Bridge Inspector may inspect bridges, major culverts and other road structures.

"**Certified Culvert Inspector**" means a person issued a certificate by COTO/SANRAL stating that he is certified culvert Inspector. A Certified Culvert Inspector may inspect major culverts and other road structures, but not bridges.

"**Certified Senior Bridge Inspector**" means a person that is a Certified Bridge Inspector who shall be a Professional Engineer with a minimum of 15 years applicable bridge experience. A Certified Senior Bridge Inspector may inspect bridges, major culverts, other road structures and special/strategic bridges.

"**Technical Assistant**" means a person whose task is to accompany the Inspector, to be a safety backup, and to provide general assistance including data capturing. A relevant technical qualification is required for this post.

"**Inspection Packages**" means a group of structures that are separately assigned to be inspected. Descriptions of the different packages are given in Addendum A.

"**Bridge**" for the purposes of the 2019 Inspections means a structure classified as a bridge as defined in TMH19.

The following size categories (sub-classifications) of bridges are also used for the 2019 Inspections:

Inspection size category (sub-class) for bridges		**Overall Structure Length (measured along road centreline as per TMH19)**
Small Bridge	**SB**	Shorter than 20m
Medium Bridge	**MB**	From 20m but shorter than 50m
Large Bridge	**LB**	From 50m but shorter than 100m
Very Large Bridge	**VLB**	Longer than 100m

"**Major Culvert**" for the purposes of the 2019 Inspections means a structure classified as a major culvert as defined in TMH19.

The following sub-classifications of major culverts are also used for the 2019 Inspections:

Inspection size category (sub-class) for major culverts		**Overall Structure Length (measured along road centreline as per TMH19)**
Small Major Culvert	**SC**	Shorter than 5m
Medium Major Culvert	**MC**	From 5m but shorter than 10m
Large Major Culvert	**LC**	Longer than 10m

"**Lesser culverts**" for the purposes of the 2019 Inspections means a structure classified as a lesser culvert as per TMH19.

Appendix F

Summary of interview responses

Table F1: Summary of interview responses

Participant Number	Question 1: Are you a senior bridge or bridge or culvert inspector?	Question 2: In which age ranges do you fall:
1	Senior bridge inspector	36-40
2	Bridge inspector	36-40
3	Senior bridge inspector	51-55
4	Culvert inspector	51-55
5	Bridge inspector	31-35
6	Bridge inspector	41-45
7	Senior bridge inspector	61-65
8	Senior bridge inspector	51-55
9	Culvert inspector	31-35
10	Culvert inspector	46-50
11	Senior bridge inspector	46-50
12	Senior bridge inspector	41-45
13	Bridge inspector	41-45
14	Bridge inspector	36-40
15	Culvert inspector	31-35
16	Bridge inspector	31-35
17	Bridge inspector	36-40
18	Culvert inspector	31-35

Participant Number	Question 3: In your experience, what aspects during bridge or major culvert inspections (following TMH19 methods) did you consider as being time-consuming, costly and/or hinder the quality of data?
1	The recapturing of inventory information, especially for bridges that have had been recently completed or have been inspected before is considered time-consuming and not necessary. Capturing the inventory photographs for larger type structures sometimes resulted in approximately 30 minutes of just walking, if one could even get to the actual point of taking a good quality photo. Access to the structure is a problem, specifically structures under flood and where one cannot cross. There is also a lot of time wastage to find a structure if it is not geotagged. The quality of data is sometimes hindered when inspecting tall structure with high piers/abutments. Even with a ladder it remains tricky to inspect and capture photos of bearings or defects on the deck soffit. Using a Under Bridge Inspection Unit (UBIU) is scary and dangerous to use. In South Africa, there is only one UBIU and inspectors must wait for the UBIU until it is available. The inspector can’t request to have the unit be available when required or at a specific time, making it very inefficient. The biggest danger with using the UBIU is the possibility of the unit being hit by a car or truck whilst in use by the inspectors. The mechanical arm holding the inspection platform crawls at a very low pace resulting in a time-consuming process.

2	Capturing of inventory photographs were time-consuming, especially for larger type bridges. Travel between structures were considered costly. Quality of data (specifically with reference to photo quality) were hindered at larger type bridges, especially bridges with very tall piers and abutments where cracks were observed. It is difficult to visually observe these areas (i.e., can't see exactly what is going on) and the zoom function of the camera used was not always sufficient to capture the extent of the problem.
3	The most time-consuming task was capturing data on the provided bridge management software. The travelling between structures was not considered time-consuming as the structures were in close vicinity to each other. The inspections itself, and specifically referring to large river bridges, was sometimes time-consuming. It was also found that capturing of data took the same amount of time as the actual inspections on-site. In terms of quality of data – some of the as-built drawings that was scanned from microfilms was poor quality and the inspection teams struggled to read these drawings.
4	The most time-consuming aspect was getting access to the culverts. Access to some areas was very easy such as in the Karoo, however, inspections in areas such as Mpumalanga where there are deep valleys and dense vegetation was problematic. In very dense vegetation/overgrown areas it is actually very difficult to find a suitable place to stand to take good quality inventory photos. Costs are directly related to the time it takes for the inspections. The more time spent on inspections, the higher the costs are for the company. The quality of photos is directly related to finding a suitable position to stand to take actual photos. The inside of the culvert is generally easy to inspect, except when it is dirty or full of water. For example, in Mpumalanga you must always wear a wading suit. You must be careful not to puncture the wading suite when climbing over a barbed wire fence. The correct equipment is required to ensure good quality data. For example, a strong headlight is always required for long culverts. It is also complex to take photos of high/tall structures. Binoculars are sometimes very difficult to use to identify defects.
5	The most time-consuming process was capturing data from paper to the software system. Driving to the bridge sites and between structures was also considered time-consuming. In terms of complex and large bridges where the Under-Bridge Inspection Unit (UBIU) is required, it becomes a problem in terms of time and cost.
6	The bridge/culvert locations i.e., travel to and from the structure to the next structure. The taking of inventory data (both photos and general information onsite) was time consuming. However, the capturing of inventory data forces you to look everywhere in and around structure so it does have value. The capturing of the four-extreme photo (elevations and approaches) of large bridges are very time consuming.
7	The most time-consuming process was getting access to the bridge sites and traveling between sites, especially in remote areas. The capturing of inventory photos and taking measurements is comprehensive and time-consuming. The capturing of data on the client's data system also requires a significant amount of

	time, especially when the software system only allows the inspector to populate the information. Other factors influencing the inspection time is long, high embankments, wide rivers, finding safe/suitable areas to park that results in extended walking distances to the structure. When an Under Bridge Inspection Unit (UBIU) is required, it was noted that the vehicle travels very slow, and it takes a long time to travel between bridges. When using the UBIU for inspection purposes, the mechanical elements of the vehicle move at a crawling speed. The reach of the UBIU mechanical arm is very short. Should the bridge have a sidewalk; the reach is even shorter. Nevertheless, it is a handy tool for inspections, and it can also be used for bridge rehabilitation purposes.
8	The capturing of field data (paper based) onto the StrumanBMS software is time-consuming and sometimes human error hinders the quality of data. It is also found that more time is spent in the office than in the field because of the latter.
9	The most time-consuming task was the collection of inventory data. Depending on your technical assistant ability, it can take even longer. How the client provides information such as the spatial data of each structure influences the entire bridge inspection process. As-built information does not always corroborate findings on-site resulting in increased time spent at that particular structure. Poor road km/distance markers make it difficult to find the structure resulting in wasting time. Bulky/large equipment is difficult to carry or take along to structure; especially for larger structures (for example where a ladder would be required). Security risks on-site remains a big concern – inspection teams must wait for or even, come back another day when there are suspect people in the vicinity of the structure i.e., wait for the environment to be safe before inspection can commence.
10	The most difficult and time-consuming process during bridge inspection is when the use of a Under Bridge Inspection Unit (UBIU) is required due to restricted access. There are only two UBIUs in South Africa and one must wait very long for the vehicle to arrive on site and move between sites. Binoculars are not sufficient to inspect certain items such as bearings. A ladder does however, work well for the latter task.
11	The capturing of data was considered most time-consuming task i.e., capturing data from paper to digital. This process was disproportionate to the rest of the inspection process. When comparisons were made, it was observed that different people and teams in the same firm were sometimes more or less efficient/productive than others. Software hold-ups/errors/bugs resulted in wasted time. The inventory requirements were also considered disproportionate to the requirements of the condition assessment. Where access was difficult, it took additional time to complete the inspection.
12	Hinderances on-site include heavy bush, dense reeds and rivers restricting access to structures. The rivers in the Western Cape are full of reeds and anywhere near the coast there are lots of bushes making access generally difficult. In semi-dessert areas such as the Karoo, access to the structures is very easy. Other aspects making the process more time-consuming includes rivers in flood, tall piers on large structures making it difficult to see/inspect bridge bearings, highway bridges spanning several

	lanes with high traffic volumes, etc. Most of the structural elements are generally easy to view except for bearings.
13	Training of new staff (job training) is a very time-consuming and an expensive process. Experienced team members spend considerable time to train new staff and to provide wide-ranging exposure to different technical problems on different types of bridges. The calibration of inspections teams is very important, even between teams in the same company.
14	Time-consuming: Doing the inventory. Measuring all the elements takes a lot of time. However, it was founded that it is the same amount of time per structure. Costly: Before inspections getting all the drawings and preparing to go out takes a lot of time. Once the inspections are complete, the processing of the data takes even more time, because the software is slow and then all the works needs to be checked. Quality of data: It is not always possible to inspect everything that is required as per TMH19. Sometimes, bridges are too high, or water ways are blocked severely. This hinders proper assessment of the superstructure or getting to piers in the middle of a river. A lot of assumptions are being made and generally it might be correct, but this could hinder the quality of the data.
15	(1) Securing access, specifically for river culverts/bridges; (2) recording of defects using the standard picklists; (3) familiarising yourself with the terrain and the structure on-site; (4) getting the structure orientation correct; and (4) checking multiple elements that are similar and/or repetitive on longer structures were considered as being time-consuming.
16	(1) Access constraints being water, vegetation, fauna etc; (2) driving to remote structures; (3) Obstruction of structure due to vegetation or built-up structures; (4) Time taken to collate inventory information; (5) Having to capture information in office, thereby increasing inventory capturing times; and (5) Noticing photos have not been geotagged once in the office.
17	It is noted that obtaining the inventory data and condition assessment (i.e., identifying defects) is a simultaneous task. Currently the industry standard bridge management software in South Africa is StrumanBMS. One of the challenges with StrumanBMS is that the inventory and condition data capturing on-site is paper based using pick lists. Capturing of information on paper on-site and then transferring information to digital is very time-consuming and prone to human error. It is suggested that visual assessments should move towards a tablet system with electronic dropdown lists to choose items (defects/remedial actions/etc.) from.
18	Re-capturing of data from field inspection sheets to BMS, capturing of none-beneficial inventory information, getting access to structures with difficult access (Overgrown, Extremely steep embankment, Large Rivers)
Participant Number	**Question 4: With reference to your answers to the previous question and in your own opinion, what technology is currently available to reduce inspection times, reduce the cost of inspections and increase the quality of data obtained during inspections?**
1	Current technology available is improved high-resolution, GPS-enabled cameras. Even cameras of high-end smart phones with the right lenses are sufficient to

	capture certain photos. It was found that having two cameras on-site (one for the inspector and one for the technical assistant) was more efficient (i.e. quicker) to complete the inspection. I have had no success in using a tablet or laptop in field whilst doing inspections. Although it would be very efficient ('the dream') to capture data live on-site, the method poses several issues/problems and difficulties were experienced whilst making use of this technology.
2	Structural health monitoring systems that can be done remotely. If the structure is instrumented, one could determine exactly what is wrong with the structure. Not sure what technology is currently available that would result in cost saving for the above aspects. Perhaps using a drone with a high-resolution camera, however, no idea what the accuracy of the inspection would be using this method. Perhaps drones could improve the quality of data where dense vegetation restricts the inspector or technical assistant from taking good quality photos.
3	The use of mobile tablets with specific software applications to capture the data on-site i.e. mobile data capturing. Where connectivity is an issue, the data can be stored locally on the mobile devise and uploaded to the cloud (ideally directly onto StrumanBMS) when connected to Wi-Fi in the evenings.
4	I am aware of other inspectors using iPads to take photos and upload directly to a bridge management system, but I have not used it personally. It is extremely time consuming to upload photos to a bridge management system as well as capturing data from paper to digital. A direct data dump would save a lot of time. The downloading of photos also takes a long time.
5	The technology is available to develop software application to capture bridge inspection data on-site, but this is currently not accepted by client. In terms of the UBIU – clients should look at procuring a better UBIU or using drones.
6	Eliminating the use of paper on site and rather working directly in a digital format for data capturing. Use of drones in the field for capturing certain visual information.
7	The current technology that is available is weather resistant tables, but it does have its limitation. High-end cameras are used, however, there is sometimes problems trying to capture good quality photographs. The time of day when photographs are taken effects the quality of the photo; shadows, over/under exposure, etc. results in poor quality photographs. The client photograph specifications should be detailed to ensure good quality photos. Drone flyovers can also give a very good overall perspective of the structure and surroundings. In terms of capturing/obtaining inventory photos and data; it could be done through well trained technical staff (not necessarily the inspector). A two-phased process could be considered where the condition assessment and obtaining inventory information is split.
8	One solution would be new software for application development on Android/IOS/Microsoft handheld devices. The most efficient solution would be to capture field information once in a digital format. More time should be in the development of user-friendly data capturing devices and software. The handling and processing of photos remains problematic due to limitations of handheld device cameras i.e. limiting aspect of this technology. When conducting flied inspections, the capturing of inventory and inspection data must typically be captured on one

	tablet/app which slows down the inspection process and it does not work well. Thought should be given on splitting the information required to be captured or having two handheld devices that is able to synchronise the information at a later stage.
9	Client should consider making inventory information available prior to the inspections. Clients should consider that inspector should rather confirm/validate inventory data and not recapture the data. Technology such as digital tablets are available to digitise the process. One could also consider using binoculars instead of ladders when required.
10	Drones and high-resolution cameras.
11	RPAs could likely be used when structures are located in areas with very high vehicle rates (bridges spanning multilane freeways) or very high/large structure. RPAs could likely be used as opposed to a Under Bridge Inspection Unit (Cherry picker) in some bridge inspection applications. Structural health monitoring systems is also technology that is currently available and can be used for remote monitoring. Crack gauges and displacement monitoring are examples of these systems. For improved quality of data, an easily accessible database for obtaining as built/record information is required. Combing as-built information with inspection requirements is very useful. Cameras have improved significantly, are GPS enabled and can take videos, etc. Digital scanners have become cheaper and is very accessible, however, this technology will likely only be required when an actual rehabilitation is planned. Scanned data can be used for current and future integration with BIM and GIS data, especially for tracking changes.
12	The use of ladders, mirrors on poles, and the Under Bridge Inspection Unit (UBIU) is current technology that is available to view/inspects tall piers and abutments. The arms of the UBIU moves at a crawling speed when it swings underneath the soffit of the bridge deck and around piers. The UBIU is also expensive. Other technological advances include cameras with a strong zoom.
13	Using Google Earth and exporting the .kmz files with all the structure locations to Google Maps on your phone is a very effective way of finding the structures in the field. Using the Google Maps interface saves a lot of time on-site. The fact that photos can be geotagged is advantages as it ensures that the correct bridges are inspected. iPads (handheld electronic tablet devices) can be used but making field notes on tablets are sometimes difficult and/or inefficient. The current paper-based system remains very convenient due to the convenience of making additional or ad-hoc notes and descriptions. If using tablets, it must have a function where the inspector is able to make notes with a stylus/electronic pen; perhaps an interface with a popup for note making and sketches.
14	Not sure. Doing the inventory by hand is the only way known. Not sure if the UAV technology can even do this. Using the UAV in areas where you can't get to will help immensely to improve the quality.
15	(1) The use of bridge inspection software applications installed on handheld devices as the selection of remedial activities for defects can take a lot of time using the

	current paper-based system on-site. (2) The use of drones on larger structures to capture defects where access is difficult. For example, using drones to capture information of the bridge bearings as opposed to using binoculars or a Under Bridge Inspection Unit (UBIU). (3) The use of drones for capturing inventory photographs. (4) Using thermographic cameras to identify bridge delamination. (5) The use of dynamic analysis instruments.
16	(1) Tablet collation of data on site, although this would need to be streamlined to ensure efficient use of a system; (2) UAV for inventory capturing; and (3) UAV for inspection of hard to access locations, to identify possible locations for further/closer inspection.
17	A digital portal should be created that is easy to customise for different client or project requirements. This would be an effective way to transform the current paper-based system to digital. No transfer of data is required using this approach i.e. paperless system. Security issues should however be considered, but with regular uploads of data to the cloud, it reduces the security risk. For example, one cannot be on-site with a laptop and populate information on the SANRAL ITIS; a handheld digital device is required. With a digital portal, one can assign a lot of additional features such as video, verbal explanation on photographs, show live feeds of issues, leave voice notes during inspections, etc. GIS systems can also be included that shows exactly where you stood when you took a specific photo.
18	Better optimised BMS, use of Mobile devices to capture BMS data directly and the use of drones for inspections of strategic structure with difficult access or project level inspections.
Participant Number	**Question 5: In your opinion, what are the most time-consuming tasks/processes of bridge inspections during physical inspections on-site and during the post-processing of the data obtained during inspections?**
1	The most time-consuming task physically on-site was capturing inventory data. The most time-consuming task during post processing was data capturing form paper to digital.
2	The most time-consuming task on-site was updating the inventory photos and data. Taking measurement/dimensions of all elements such as high piers, abutments, length of the structure, etc. is time-consuming. The most time-consuming task during post processing was entering all the inventory data into the digital system (StrumanBMS software), especially when no as-built drawings were available.
3	The most time-consuming task on-site was getting access to large structures, especially structures spanning rivers. Older structures took longer to inspect because it generally had more problems/defects to identify and rate. In terms of post-processing, capturing of data was the most time-consuming process and software bugs on StrumanBMS delayed the process even more.
4	The capturing of the inventory data took a long time. If inventory data is captured once, it is not necessarily required to capture it again. The question was posed whether a 5-year period is long enough to re-capture the data. It might only be required to review inventory data in principal and only update data that looks or is wrong. The inventory data must be provided to the inspector in advance. Condition

	assessments must however be done independently so that the inspector is not influenced by the previous person.
5	The most time-consuming task on-site is looking at the bridge bearing with binoculars. Generally, high or difficult access results in a very time-consuming inspection. In terms of post processing, the required software application (StrumanBMS) is slow to use.
6	It would be walking the distances to get appropriate photos for large bridges. Currently working on four different client bridge management systems. The system's generic pick lists used for data capturing are sometimes outdated or too generic to describe specific information. For example, there is currently no generic item in the pick list to describe Western Cape Government standard parapet/balustrade. Some other technical terms are also not current.
7	The most time-consuming task is data capturing after the inspection. Having previous inspections at hand could speed up the inspection process. Getting access, physically walking through the bridge site and inspecting all the critical items is a time-consuming process. Perhaps using the same inspector could be considered for the same bridges in the future.
8	Access to the structures such as climbing over fences and using a rope to climb down very steep embankments and canal slopes, etc. Capturing of inventory data takes a long time.
9	Capturing of inventory. Software limitations with client's software. Road distance/km markers on site is sometimes missing.
10	Taking measurements and dimensions of structures on site for inventory purposes is very time-consuming compared to the actual visual assessment that is relatively quick. The StrumanBMS software is not user-friendly and very time-consuming to use.
11	Capturing inventory data physically on-site is considered the most time-consuming process. In terms of smaller bridges, the condition assessment is usually quicker than capturing all the required inventory data. In some cases, the technical assistant is inexperienced and takes longer than the actual inspector to complete their works. Access restrictions such as game fences or dense overgrowth slows down the inspection process. Inspections in areas such as the Karoo (dry, flat, no high embankment, limited vegetation) is very quick because of easy access to the structure. High crime zones and dangerous areas increase inspection times. Capturing data from paper to digital is the most time-consuming post-processing task. However, recording information on paper on-site is generally very quick and effective. When digital handheld devices are used, poor connectivity to upload information to the cloud is a limiting device. Even of the information is stored locally in the device, the risk remains damaging or losing the device which will result in a lot of rework. It is very important for inspections teams to be disciplined in having a systematic approach to improve efficiency.
12	On-site, access to the structure and driving to/from structures are considered the most time-consuming tasks. However, if structures are grouped together for inspections, it accelerates the process. In terms of post-processing, the most time-

	consuming task is the data capturing from the paper notes onto the bridge management software. It was concluded that capturing work in the office took the most time during the bridge inspection process. Learning the software programme is a good start to improve the efficiency of capturing the data. The software programmes used for bridge inspections are generally of poor quality and not user friendly. The experience of the staff used for capturing data also contributed to the efficiency of the process, but big variations were observed between capturers. When inspectors are familiar with the systems, it makes the entire process much more efficient.
13	It depends on the size of the bridge. The time spent on site is very limited for small bridges. The relative time is based on the complexity, size and number of defects found on the structure. In terms of post processing, the inspection team must stay organised. For example, filing of data must happen on-site to recapture the information at a later stage without introducing human errors or delays as a result of misplaced/missing information.
14	(1) Capturing the inventory data from inspection sheet is time consuming, especially if the data is filled in partially; (2) You also must deal with people's handwriting which are sometimes so bad and therefore trying to decipher inspection/inventory sheets takes time; (3) Getting to know the software will take time with new data capturers; (4) The StrumanBMS software is a slow program, especially uploading the photos. The whole process of uploading one structure in StrumanBMS takes approximately 1 – 1.5 hours. That is without the inspector checking the data uploaded; (5) The checking and verification of the data in StrumanBMS also takes time, it therefore becomes a back-and-forth process, and this will always be there. You have to check your work.
15	(1) The use of current paper-based data sheets and picklists for inexperienced inspection teams is very time-consuming i.e. it is takes several minutes to find the correct item/activity/defect/remedial action on-site having to page through all the data sheets. (2) Getting access at a river structures, specifically where boats are required. (3) Checking of multiple similar elements on long structures i.e. having to walk to every pier, inspect each span and abutment, etc. (4) It is very time-consuming checking long and multi-cell culverts, especially when openings are overgrown/blocked and requires clearing. In the office, data capturing from paper onto the StrumanBMS software was very time-consuming. The codes for the remedial activities are sometimes incorrect and other software related issues result in time wastage. The consistency between the capturer and the inspector i.e., miscommunication can also lead to quality control issues resulting in more time required to complete the works.
16	Similar to above iii.
17	On-site: Access to the bridge/major culvert is a time-consuming task and can become tricky, especially on passes. Sometime culverts take much longer to inspect than bridges due to access. This is however an issue than won't go away. The most time-consuming task is capturing data from paper to the electronic system. A digital portal with dropdown/tick option should speed up process. Searching for the correct

	items on the current paper-based picklists can take a lot of time on site. A digital system can save 20 – 30 % of the time of capturing directly on digital.
18	Walking to take all the inventory and inspection photos especially on large structures and then labelling the photos taken and assigning them to the correct defect and remedial actions. Then Finally repeating this process to capture his from the field inspection sheets onto the BMS.
Participant Number	**Question 6: When conducting principal inspection per TMH19, the inspection team is required to capture inventory photos for each structure. In your experience, are capturing inventory photos during principal inspections a time-consuming process? In your opinion, would the total duration spent at each structure be reduced if the capturing of inventory photos were not required? If 'yes', please explain how much time could be saved during inspections. If 'no', why not?**
1	Yes. Especially for structures that have been recently inspected. Yes. It would be reduced, but not by much. This is because the inspection of certain elements happens simultaneously whilst capturing inventory photos. There could perhaps be a 25 -30% time saving per structure.
2	Yes. It is time-consuming on medium to large structures, but not on smaller type structures such as small bridges and culverts. Yes. The total duration would be reduced, but it would depend on the structure size. There could be a timesaving of approximately 10-15min per structure for medium to large bridges should inventory photos are not required.
3	The capturing of inventory photos does take time, especially when up/down stream photos are required for structures found in watercourses. The inspector takes inventory photographs to get a holistic picture of the bridge before conducting the actual inspections. This could be considered as time consuming, but it is time well spent.
4	Yes. It is time consuming. Measuring and taking dimensions of the structure is also very time-consuming. Yes, it would be. It would take about 1/3 of the inspection time away for each structure. The inspector must sometimes help the assistant with taking measurements, etc.
5	No. Capturing of inventory photographs for culverts is not considered a time-consuming process and it would not affect the time required to complete the inspection. However, for bridges it would definitely make a difference due to the number of photos required at each bridge.
6	Two-fold perspective: (1) Capturing the inventory photos forces the inspector (or technical assistant) to go all around the structure to capture the required photos, but simultaneously to identify material and structural defects. (2) It might appear as time consuming, but there is a lot of value in the process. No, for smaller type of bridges and yes for larger type of bridges. One still needs to orientate oneself around the structure to understand the behaviour and defects of the structure. One still needs to look at all the main items on the bridge such as the deck, joint, abutments, etc.; all which contributes to the total duration spent at the

	structure. However, the duration spent at a structure increases significantly when photos were not geo-tagged, and one needs to go back to the structure to recapture the photo. It is also time consuming when the camera GPS does not or takes long to lock-in. An interesting observation in Cape Town area was that between 12:00 – 12:30 PM, the entire area seemed to be a dead spot in terms of locking in the GPS.
7	The aspect depends on how the inspector utilises his assistant. It also depends on the type of bridge. It is estimated that the inspection team can save approximately 15 minutes per structure. The importance of capturing inventory photographs during principal inspection is noted. Clients could consider completing the inventory aspect of inspection in-house/departmentally.
8	Yes. All the photos are taken with one camera i.e., the inspector takes all the photos (inventory and defects). Photos that take the longest time to capture is elevation photos, especially for longer bridges and where dense vegetation is present. It can take approximately 10-15 minutes additional to take these photos per structure. The Client should consider doing inventory once if it was done well. Thought should be given to possibly splitting inventory and inspection processes. One should get better results from the processes if they are split. It is considered non-critical to update inventory data every 5 years. Inventory data should preferably be sourced from as-built drawings which are inherently more accurate that field measurements and observations. Structure owners should be careful not to override accurate inventory data (from as-built drawings) with less accurate field measurements or observations. This data should be made available to inspectors in advance for preparation purposes.
9	No. Capturing all the inventory photos is a very quick process for culverts. It is anticipated that no time will be saved if this aspect was removed from the inspections.
10	No. Capturing inventory photos is not time-consuming. No. The inspector needs to take the photographs anyway and it is always useful to go back to the photographic evidence and reflect on decisions/ratings. Approximately 80% of the most recent visual bridge inspections could have been done remotely from the office using only drone footage
11	The most time-consuming photos to capture is the elevation photographs of large/big bridges. The inspector or assistant is sometimes required to walk approximately 1 km to take an elevation photograph. In some cases, bushes and dense vegetation prevents the capturing of good quality photographs. The total duration of an inspection will not be reduced if inventory photographs are not required considering that the inspector needs to go to all the location of the bridge for the condition assessment; except for the elevation photographs.
12	No extra time is used to capture the inventory photos and therefore it won't result in any timesaving should it be removed. The inspector needs to walk around the structure anyway and capturing of inventory photos happen simultaneously with the condition assessment. The only photos that can take a long time is the elevations of large bridges. It takes approximately 5 minutes to capture all the inventory photos for a medium sizes bridge if doing it is done at a very fast pace.

13	No. The capturing of inventory data happens concurrently with the main visual inspection. However, if the inventory requirement was removed from principal inspections, the assistant could immediately start assisting the inspector without having to take photos and speed up the bridge inspection process on site.
14	No. Photographing the structures is just a click of the camera. Its not time consuming at all. What takes time is measuring all the elements. You must take out measuring wheels, measuring tapes and lasers etc and once complete with the measuring, you must record it. For me that takes time, not taking the images.
15	It depends on the size of the structure. Capturing inventory photos for culverts is a quick process unless there are access restrictions. It sometimes takes time to get to the right/optimum position to capture a good quality photo. For larger structures, the process is more time-consuming.
16	It depends, on a few factors: (1) If the structure being inspected has a few defects then the assistant would spend more time than inspector on the structure. In this case you may save time overall by reducing the time of the assistant at the structure. You could save, +/- 15min per medium sized bridge. (2) Inversely on structures where there are significant defects, not much time may be saved.
17	Yes, it is considered time-consuming. Most of the walking take time (especially for larger type bridges) takes place when capturing inventory photos. Some elevation photographs take a long time to capture. When inspecting large bridges, at least 50% of time spent at the structure can be removed when the inventory requirement of the process is removed. Inventory photographs are however, ideal for monitoring purposes and should still be captured.
18	**Yes, time would be saved especially on larger structures. 5 min per structure on average for smaller structures and 10-30 min for larger structures.**
Participant Number	**Question 7: Have you made use of RPAs for bridge/ culvert inspections? If 'yes', please share your experience. If 'no', why not?**
1	No, I have never used it. The cost of drones is too much at this stage. The time and expense required to train, procure and fly the actual drone does not seem feasible at this stage for it to be used as a supplementary tool for bridge inspections. I have observed someone else using a drone for bridge inspections, but the drone seemed fragile and was very expensive.
2	No. Drones are not accessible/available at the company and they are pricy i.e. a cost issue at this stage. Not familiar with this technology.
3	No. Although the company owns drone to provide additional information to clients, problems were experienced in terms of pilot licences and flying in open spaces. These limitations and the strict regulations currently prohibit and prevent the use of drones for bridge inspections. It is noted that should the regulations be better understood, one could perhaps speak to the relevant competent authorities to make amendments to the current regulations.
4	No, not yet. The company does not have a drone at their disposal. If the opportunity was however there to make use of a drone, no person in the company can legally operate the drone. It would also be considered an additional cost at this stage. That

	said, if all the above was in-place, and specifically referring to culvert inspections, it would still not be used. The inspection process could even take longer if both drones and normal conventional processes had to be followed. For large bridges where boats are required, drones could possibly be considered feasible.
5	Yes. It was crucial to use a drone to gain access for the inspection of the Komati River Bridge. A Google 360° camera was mounted to the top of a DJI Mavic Pro drone to capture imagery of the deck soffit and bearing. The drone and camera were controlled independently by two operators i.e., pilot and the inspector. The process worked very well.
6	Personally, not yet due to not having a remotely pilot licence or drone to experiment with. If he had a drone though, he would have experimented with it.
7	No, not personally. However, he does have knowledge of certain drone limitation such as when flying underneath a bridge, the drone camera, lighting and losing signal between the drone and pilot could cause problems during the inspection.
8	Yes and no. I worked with a company that used a drone for bridge inspections of approximately 30 bridges. The idea was to view/inspect difficult to access elements such as bearings and expansion joints. In most cases it was too windy, and the camera could not point upwards to view the bearings. In most cases it was proved that the use of a drone for these inspections was not feasible. On another project it was considered to use a drone for safety/security reasons in areas where it is considered unsafe for bridge inspectors i.e. near informal settlements or near homeless people. Other issues such as technical complications with the drone and the pilot's licence that expired resulted in the drone not being used. Even then it would still only be a proof of concept and the results of how effective it would be is unknown.
9	No. While the equipment and UAV accredited pilots may be available within our company, the process required to obtain "air right" and approvals is extremely time consuming and would not be able to be achieved within the anticipated budget. Perhaps clients could either package approvals prior to the contract award, or a provisional sum could be made available to cover costs associated with this process.
10	Not for bridge inspections as SANRAL is opposed to using drones for bridge inspection purposes. The firm does, however, have a UAV which was previously successfully used for dam inspections.
11	No not personally. However, colleagues have made use of UAV's. The firm has licenced pilots and high-end drones. The ability of an UAV and the pilot to get the quality of photograph required by the inspector is a limiting factor. There are also only few bridges in South Africa that is considered inaccessible to capture photographs of, for example, the bearings. It must also be noted that general pilots (pilots without a bridge design background) do not go through the same thought/cognitive process as the bridge inspector.
12	No, however, it would be interesting to see how it would work. The opportunity to use a drone for bridge inspections never presented itself and it was never a requirement from the client.

13	No. It is considered too expensive at this stage and a pilot with a licence is required to fly it legally for commercial use. Having a pilot as part of the inspection team (i.e. three people as opposed to two) could result in more costly inspections due to the increased size if the team. It would also be expensive (training, licences, etc.) if the inspector or assistant have their own licenses.
14	No, the company has never even tried it. This is new technology. Do not know of one person that ever used it, so it is very new.
15	No, due to the costs related to procuring a drone. The entire bridge inspection process may be more expensive due to the need to hire or employ additional people such a qualified pilot (unless the firm already have inhouse capabilities).
16	No, no successful trial projects in South Africa that I'm aware of.
17	Yes, I have recent and personal experience with using RPAs for bridge inspections. Many bridges require an Under Bridge Inspection Unit (UBIU) to gain access to specific parts of the bridge. The client asked that the consultant experiment with UAV's instead of UBIU. A big issue was handling/controlling/flying the UAV under the bridge deck in terms of losing signal. When the UAV lost signal, it automatically flew 'home'. The initial idea was using VR goggles or using a high-definition screen on-site to view defects live. Based on the experiment, I am not convinced that the inspector will be able to see/identify all the bridge defects. The question was posed whether you would be able to gauge cracks widths on video footage or photos. Nevertheless, I am still in the process of examining the usefulness of RPAs for bridge inspections. One major concern is whether the inspector will have the same gut feelings when assessing the bridge remotely using drone footage as opposed to being on-site conducting the assessment.
18	No, I have not had the opportunity (Cost, licencing, beneficial)

Participant Number	Question 8: Do you know of inspectors, clients and/or firms that have made use of UAVs for bridge/culvert inspections? If 'yes', please elaborate on their experience.
1	No. I am aware of firms using drones for civil infrastructure progress monitoring on site and advertising.
2	No.
3	Yes. Aurecon – limited knowledge to their experience.
4	No.
5	No.
6	Yes. AECOM. Terry February (RPL) Drone Services is frequently used to monitor construction progress.
7	Yes. A reference was given of a firm that has made use of drones for bridge inspections.
8	No.
9	No.
10	No, not in South Africa.
11	Yes. Previous question.

12	No.
13	No.
14	No.
15	No.
16	No.
17	See above.
18	Yes, SANRAL presented an example case study done at project level. Aurecon has drones and licencing I believe; however, I am not aware if they have used it for inspections as of yet.
Participant Number	**Question 9: What is your opinion about using RPAs for bridge/culvert inspections?**
1	There may be some application in using drones for bridge/culvert inspections, but it will not replace a comprehensive physical on-site inspection. The use of drones will not result in the elimination of an inspector in the process. It would perhaps save some time during the inspection process, especially for larger type structures to capture photos of bearings, underside of deck, etc. but the issues remain; for example, bearings need to be physically touched or an inspector needs to be at arms lengths to touch the structural element when deemed required. The drone battery life is a limiting factor, and the process is data hungry.
2	It will save some time on capturing inventory data and one could possibly obtain better quality of data on site using a drone. For example, you can review the drone footage afterwards (in the office) to revisit and/or make better decisions post inspections. Inspectors can rate structural defects off-site at the office when he has more time to deliberate the DER rating per defect against the photos that were captured during the visual assessment, i.e., the inspector captures photos, make notes and rates each defect afterwards in the office. If UAV can give you a better picture of the structure and the defects, one might get more accurate results using this method.
3	It is a good idea. For example, it could be used to look at bearing on structures with high piers/abutments and could possibly replace the use of ladders in most cases. Drones could improve the quality of inspections in terms of recording video footage and replaying the video at the office if the inspector was uncertain/undecided about specific items.
4	See above.
5	Drones should be used for inspections. It works well for this purpose as it speeds up process.
6	Not opposed to using this technology i.e., favourable. One of the biggest benefits might be in terms of large bridges over polluted rivers or access to inaccessible areas as opposed to using Under Bridge Inspection Unit (UBIU) and/or hiring a boat. There are currently corporate restrictions and special permissions required before inspectors may use UBIU due to safety concerns for the inspector.
7	There is merit is using drones for bigger bridges where a UBIU is required. The UBIU is a problem in terms of keeping the vehicle certified and it is expensive to

	use. Taking this into account, there is definitely potential in the use of an UAV. Drones can be used as a supplementary tool to capture inventory photos, fly over/along/under the structures and capture photographs/video footage of critical areas. Other technology is also available such as monitoring instruments and sensors such as GPR scanning, vibration scanning and even the use of the accelerometer check using a cell phone. Perhaps non-destructive testing apparatus could be attached to drones.
8	Even with limited exposure with the use of drones, it is not considered to be the answer for bridge inspections. There are too many practical limitations such as flight time, reach, etc. What the drone can actually access is also questioned i.e. can you access everything on a bridge with a drone, can fly over/under the structure, inside a culvert without losing GPS signal, etc. UAV's will likely not significantly take over any of the processes. No big changes anticipated for bridge inspections with reference to the use of drones.
9	It is a good idea. There is some merit to investigate the use of drones for bridge inspections, particularly for larger structures.
10	The use of RPAs for bridge inspections is a possibility.
11	UAV's have its place and could be useful in certain scenarios and when needed, especially for very complex and high bridges. There is also some value sense in terms of scanning a bridge using a UAV.
12	The inspector will always need to visit the bridge site. There is nothing like observing the bridge in person and getting a holistic view of structure within its surroundings. Being physically on site allows you to see how green the vegetation is, how tall is the structure is, inspect cracks from different angles and question the reasons for the defects. It is also not clear whether there would be any cost-savings, especially for small structures. However, for a big structure, having a drone on standby to replace a boat or an UBIU could have its advantages, but it will still have a cost increase. Nevertheless, the cost can be warranted for special, specialised inspections. In this case, the inspector will have to give the pilot instructions re. where to fly. If a pilot, a bridge inspector and an assistant must be on site, it will increase the inspection time and cost. In perhaps 5% of the cases where access is impossible, a drone could be considered feasible.
13	The use of drones should be piloted on three bridges (small, medium and large). In terms of large bridges, drones could perhaps replace the need/use of an underbridge inspection unit (UBIU). The use of drones for smaller bridges is considered limited. Drones would be excellent for capturing good quality inventory photos due to its ability to rapidly move to a position to capture complete elevation sections of a bridge (i.e., fly back far enough) and to view the structure and structural elements from different angles.
14	It is considered a good idea, especially where you can't see or reach elements of a structure. Using a UAV to inspect the soffit of a superstructure over a big river will be of immense help. Thinking back on the inspections that have been done before one could have been assisted by means of a UAV. He had to manoeuvre in a boat to get to the superstructure of a big river bridge. Once he was underneath, he had to

	look through binoculars to assess the soffit and the bearings. It is a difficult task and there is no way that you can accurately assess the superstructure soffit or even look at the bearings and at the same time keep the boat still. Yes, you will pick up a major issue, but the quality of your work is not perhaps quite there, and a lot of assumptions are being made.
15	Drones can be useful for both capturing inventory data and identifying defects, especially when access is difficult and as opposed to using a UBIU.
16	(1) Would be a great asset if enough time is invested in the technology. (2) Pre and post use of system needs to be enhanced.
17	It is definitely an existing prospect, but I am not yet convinced that it is feasible. The mobility and technology of UAV's are not yet suited and able to identify defects and conduct evaluations. As far as mobility/feasibility goes, and based on the recent bridge inspection experiment, I cannot determine the quality of the work. There is also uncertainty whether you could back your professional opinion and whether you can rate a defect using only drone video footage.
18	I believe there will be a use for RPAs in bridge/culvert inspections, but not with current technology, pricing and legislation for network level inspections. Project level inspections are currently more feasible.
Participant Number	**Question 10: How do you foresee bridge/culvert inspection happening in the future i.e., 15 years from today?**
1	Cameras and GPS technology are getting better, and data management will continuously improve. Currently, the existing information on older structures is difficult to find. This will change for new structures in the future as information is better managed and accessible. Bridge/culvert inspections will largely remain the same with people being required on-site. The bridge inspection process could improve in terms of efficiency by supplementary equipment.
2	There is a market for RPAs in the industry, however, structural health monitoring devices might even eliminate the need for visual inspections in the future. The structure can be monitored from the convenience of your computer in your office resulting in the need for visual inspections to decrease.
3	In the next 15 years, it is envisaged that the regulatory 5-yearly principal inspections will be replaced with an automated process; perhaps a pilot using to drone to fly-over and capture imagery of the structure for the inspector to conduct the inspection at the office without having to go to site. Sensors will also be installed during the construction bridges for remotely monitoring purposes i.e., structure health monitoring. It is envisaged that manual on-site inspections will only be required every 15 years and the 5-yearly inspection will be done remotely.
4	It depends on the specifications of the client. Inventory data changes very little over a long period of time. After say two rounds of inspections, the inventory should be updated and correct. Sometimes the structure numbers and/or km location are incorrect and should be verified and updated if incorrect. The client should only consider doing condition assessments in the future, leaving the inventory data out if deemed correct. Drones are not feasible for most culverts. Future inspections should

	likely remain the same as it is today. For large bridges over rivers and busy roads it might be useful. I am sceptical on the use of drones for culvert inspections and doubt whether inspections would look or be done any different in the future.
5	The use of drones and other remote monitoring devices such a strain gauges, instruments, etc.
6	Possibly using drones as a pre-screening tool before inspectors go out for physical inspections. There is a lot of scope for monitoring inspections to observe/monitor issues such as minor scour problems, problematic embankments, etc. Time lapsed view of these issues might be of value. Drones can also be used as a pre-screening tool after each flood events to identify/quantify scour and embankment issues.
7	In South Africa, the frequency of inspections should be revised. More time should be invested in life cycle modelling of the structures. Certain components should however be inspected on a routine basis. Consideration should be put into splitting elements that must be monitored more or less frequently.
8	One must move towards autonomous processes by using instruments during construction and post construction. One must look at the behaviour of the structure during construction using instruments. The future and long-term solution is the use of instruments built into the structure for observations and data collection. If a drone cannot detect the defects on its own, then people will always be required. Simple observation for humans such as crack detection is a real struggle for drones. On another project a machine learning application was tested to detect roads widths for a Pavement Management System, but it proved to be very complicated to teach the software what a road is. The accuracy was about 70% for identifying the roads correctly and then also an accuracy of 70% for the road width. It also proved to be very expensive to teach the software and improve accuracy. It is envisaged that bridge inspection will not change too much in the next 15 years. Software will improve to make tasks such as capturing data easier, and drones will probably help with access. Competent engineers/bridge inspectors will still be required to do analysis and make engineering decisions. Instruments and software will be used in the future to manage bridges, but this will likely be post 15 years. Strain gauges, deflections, vibrations etc. data loggers, processers will be used to detect change in normal/predicted structural behaviour.
9	I am curious to see any future prospects in terms of using drones. However, it doesn't have to be a drone, it can be digitising the process through other means as well. Equipment and software is expensive and usually data hungry making this option less attractive, but it will likely become more affordable in future. Making use of RPAs for bridge inspections is very expensive.
10	It is envisaged that inspection will make use of technology where possible. There is a lot of technology currently available to improve the process.
11	Software (such as AI) will likely become available to assist with searching for defects. This technology is likely to progress/mature much more in the future. However, technology will not replace the judgement of an experienced bridge engineer. AI could only be used to assist the inspector, and this will likely become a bigger trend in the future. Technology with handheld devices will also improve to

	eliminate duplicate and repetitive work. The inspection team should likely be able to use photographs to log measurements. Lidar scans is considered very useful, but its application in limited in terms of the large data required. This would typically not be feasible for network level inspections.
12	Bridge/culvert inspections will happen much the same. Personally, I do not see drones being used except for large structures or structures that are difficult to access.
13	Future inspections will be more automated (i.e. using iPads to capture data once in the field) and it will become more detailed (due to more information becoming available during inspections). The method of inspections will also become more mature. There will, however, always be a requirement for the inspector to go to site and one cannot move away from that aspect. Part of bridge inspection is discovering where and what the problems and issue are, if any. It is an on-site process, and I cannot foresee that it would feasible to replicate the process in the office as you are limited to the video footage.
14	He is of the opinion that an UAV will play a major role; however, it is not foreseen that it will only be a UAV on site. He thinks it will be both. You can't get a 'feel' of the structure and its surroundings from a video or camera.
15	All technical and practical issues re. the use of tablets and software applications will be resolved in the next couple of years. One could possibly be using drones where access is limited. The use of thermographic cameras attached to drones might also be a possibility.
16	Semi-autonomous inspection/inventory will take place. However, the professional aspect of inspections will definitely be around for the next few decades.
17	The process will be digitised in the future. For example, one can simply look at advancements of BIM. There will also be an integration of different technology such as drones, BIM, mobile tablets, etc. The human factor will be reduced for repetitive tasks to lessen errors. It is envisaged that biometric systems will be used to ensure that the correct person/inspector captures the data. It is envisaged that at least 50% of time will be saved when data is captured directly on digital i.e., paperless.
18	Absolutely and hopefully more efficiently and rigorously.
Participant Number	**Question 11: What is your understanding of the term "autonomous bridge/culvert inspections using UAV's"?**
1	Simply using technology such as drones to supplement work on site. Technology at this stage is not intelligent enough to replace people and experience.
2	An UAV that is programmed to inspect certain elements at a specific frequency.
3	A drone pilot will fly-over the structure on a pre-determined flightpath and the inspection will be conducted by the bridge engineer in the office. The firm is currently investigating point cloud scanning and the use of algorithms to identify cracks in the structures. This process could possibly be autonomous should one incorporate intelligence into the post processing of the data.
4	It is where a standard procedure is written for inspection of a culvert in/outlet and a standard flight path is programmed to position the UAV for taking videos or photos. A person will still need to take the actual photo when the drone and camera is in

	position. Drones won't be able to do it. Fly-by's can be done to take videos of the structure and focus on features such as joints.
5	A drone operated by a pilot to act as an eye for the inspector. In the future, it can perhaps be used to measure cracks.
6	Removing the bridge inspector physically from the site i.e., removing the people from an unsafe environment and replacing what would have been observed on site with video footage.
7	The term refers to a more photographic inspection where someone takes photos, and the inspector assesses/analyses the structure afterwards using the drone footage; or live on-site while the pilot is flying the structure. The latter approach will enable the inspector to request the drone/camera operator for example, to zoom in at a specific area or provide more detailed footage/information. It should be noted that autonomous inspections could pose dangers to the client and inspector in terms of labiality.
8	Send a drone out and allow the software to determine the required answer.
9	The use of some sort of drone doing a portion or the entire inspection.
10	The term refers to the inspector not always being required at the bridge site. The advantage of using drones is that the pilot does not have to be an accredited inspector, therefore more bridges can be inspected in a shorter period. The latter will require the inspector to compile a detailed scope of works for the pilot for the imagery to be used for a remote inspection. An example was given in terms of remote dam inspections: Firstly, the inspector goes to the dam site to get a general feel. Thereafter the inspector pre-identifies areas where more detailed footage is required. Most of the inspection works can be completed remotely. Drones enable the inspector to view elements from much more angles and perspectives. As soon as we start using this, the technology will also improve very quickly.
11	This term refers to the use of an UAV which can be controlled remotely to fly, record video footage and capture photographic information that can be used by the inspector for post-processing and analysis of the captured data.
12	The terms refer to either a drone and pilot being on-site during the inspection or the pilot controlling the drone remotely off-site.
13	It refers to a pre-programmed drone flightpath where the pilot is responsible to take-off and land the drone.
14	It means that the UAV will fly around the structure whilst you sit at your computer or sitting in your car. The UAV will collect all the data, i.e. taking a video of the structure. The inspector will not walk around the structure. He/she will then only dissect the data on his computer.
15	Never heard completely autonomous bridge inspection system or process. The term could perhaps refer to the automatic detection of defects, but not necessarily the assigning of remedial actions for defects. The bridge engineer/inspector is still required for the latter.

16	The semi-autonomous process of bridge/culvert inspections.
17	The terms refer to the incorporation of drones and ways to conduct inspections without the inspector being on-site. The inspector must however still be on-site to identify the defects and reasons for the defects.
18	Inspections are complete by RPAs with very limit or no input from an operator during the inspections.
Participant Number	**Question 12: Did you think that bridge/culvert inspections can be conducted semi or completely autonomously? If 'yes', what would your role be as the inspector? If 'no', why not?**
1	I don't see it being completely autonomously. People with some experience in structural design will always be required to go out to the bridge/culvert site. Data files are becoming very big which might pose a problem to structure owners.
2	Perhaps semi autonomously. Drones would be able to pick up defects, but an inspector is still required to explain the defect. Detailed inspections must still be done by a competent bridge inspector physically on-site
3	Yes, but only semi autonomously. The role of an inspector will be to do quality/spot checks. Depending on how the data was collected, the inspector will do the assessment of the structure based on the photographic/video imagery obtained by the drone. The automation process is not taking away the work of the bridge engineer, it merely enables the inspector to do more inspections, save more time and deliver better quality of work. It is considered an augmentation of the process.
4	Yes, semi autonomously, but not completely autonomously. The role of the inspector would be to look at the video footage whilst the drone is flying (i.e. live view of footage). The inspector will have to take control or instruct the pilot when he identifies defects in order to take more detailed video footage of these areas/defects.
5	Semi autonomously. The role of the inspector would be to vet and interpret the information.
6	Largely yes for monitoring highly visibly issues. If a structure is a good condition – it could be argued that an inventory sweep is sufficient. However, if a structure is in bad condition, an experienced person needs to be able to decide and needs to be physically on site. For example, a collection of photos of close-up views of cracks means nothing. One must have a holistic view of the issue and one must have sufficient experience to make complex or high-risk decisions. Can one really get sufficient context from video footage to make a sound engineering decision?
7	Semi autonomously. The inspector will still need to go out to the bridge site. Drones could however assist with logistics through providing certain information (such as access issues, safe areas to park your vehicle, etc.) in advance. Inspector will remain accountable for their assessment.
8	Semi-autonomous for gathering and capturing certain data. The interpretation of the data will still be done by the inspector. I am unsure how well the visuals will be from the drone footage. UAVs could possibly be used for screening purposes to determine whether it is actually required for the inspector to go out to site.

9	Yes, semi-autonomously. However, there is definite merit for the inspector to be at the structure during inspections, especially when the structure is in poor condition. An inspector is required to make on-site decisions re. the condition of structural elements that is perhaps failing or unsafe to use. Some limiting aspect with drones is that the cameras can't point upwards to look at the deck soffit or bearing. I am not able to fully trust/rely on the capability of a drone just yet, but it is perhaps good for a preliminary assessment.
10	The drone and software can't think. The inspector will have to analyse the data and determine the condition as well as propose remedial actions.
11	No as it is considered necessary for the inspector to be on-site. At some level the inspector should be on-site to exercise his/her engineering judgement. When being physically on-site, the inspector incorporates additional aspects such as the sounds (e.g. when a vehicle drives over a joint), vibrations and environmental factors near the structure. That said, a lot of the work can be done autonomously, but only as a quick check. It is considered that the more routine the structure and inspection, the more it lends itself to being done autonomously. Drones can therefore definitely be used as a supplementary tool. Complex and wider ranging aspects such as the interaction of the structure with the river and the reasons why a river is behaving a certain way cannot be autonomously captured and analysed with technology.
12	No. The inspector needs to be physically on-site to get the feel of the structure and the surrounding environment (temperature, traffic, use of crack gauges, etc). Drones could possibly be used for an initial check and for general purposes.
13	The technology is not mature enough for completely autonomous bridge inspections. However, pilot studies should be conducted to test the possibility of semi-autonomous inspections. It should be noted that being on-site provides the inspector with a lot of context with respect to the actual site and structure. Capturing of information in an autonomous manner is fine, however, interpreting and analysing the information solely based on photographs/video footage will be very difficult.
14	Yes, but only semi autonomously. The inspector will be on site with the UAV. The inspector will get a 'feel' of the structure and the surroundings of the area. He can inspect the elements that is easily accessible. The inspector will use the UAV for the elements he can't get to.
15	Yes, but semi-autonomous only. Drones could be used to detect defects more effectively and perhaps even the extent of the defects. However, the role of the inspector will still be to capture the degree and relevance of the defects as well as the remedial measures. Drones won't be able to capture the relevancy of a defect.
16	Yes, the Inspectors role would be enhanced by reducing 'unable to inspect' aspects of certain bridges.
17	No, but perhaps semi-autonomous. The inspector can be at the bridge and use a high-definition screen to view defects live. Automatous features at this stage are hindered by limiting factors with drone technology (not mature enough) and software limitation. Inspector will always be required on-site.
18	Anything is possible in the future, however currently with the available technology I believe UAV's and technology can only assist the bridge/culvert inspector and not

	replace them completely. As technology and methods improve inspectors will start verifying information rather than capturing.
Participant Number	**Question 13: In your opinion, how can the client assist bridge inspectors to improve the efficiency of bridge inspections?**
1	The client should reduce tasks that could be considered or is potentially redundant. The client could also reduce the requirement from the inventory side. It is considered unnecessary to recapture static information. The handling of the position of the structures on GIS could be improved. The client should set guidelines of inspector accreditations required for their bridge/culvert inspections. Procurement methods also effects the quality of inspections.
2	From an inspection point of view, the efficiency could be improved by removing the requirement to capture inventory data. Perhaps a drone can be used for this. In terms of data capturing, the use of tablets could be considered, but I believe they don't work well.
3	The client should provide all the existing information of the bridge which will make the inspection process easier. It is considered that more data/information will improve efficiency of the bridge inspection process. The possibility of a StrumanBMS mobile app could lead to a cost saving by at least a third of the original time.
4	No, not really.
5	The client should provide better capturing software and allow the consultant to use tools such as RPAs.
6	In terms of inventory photos – inspections can be more efficient if the inspection team does not have to update the photos every time or there should be another way to update these photos. An update to the inventory pick lists is required to save time in terms of describing/or picking current standard structural elements such as the types of balustrades, bearings, joints, deck types, etc. Use updated specific lists rather than generic lists. Not of lot of issues were experienced with inspection process. There were, however, safety issues/concerns at certain locations in the Cape Town area during inspections. For example, at the R300 near Mitchell Plain and at the N2 near the Bonteheuwel pedestrian bridge. The very busy roads in Cape Town also made the inspection process unsafe as opposed to 20 years ago. It is currently far more dangerous to do inspection work along/over busy roads due to the increased vehicle numbers. It is very unsafe for a people to physically cross the N2 or R300 on foot. The inspection of culverts on dual carriage ways or in the vicinity of homeless persons were also problem due to security concerns of being mugged, assaulted or being trapped inside a culvert as a result.
7	Clients could consider providing the consultants with more background information. Clients could also consider reducing the inspection frequency i.e., requiring a more detailed and comprehensive inspection, but less frequently. Clients should also identify 'problem' structures and monitor these structures more in depth and frequently.
8	The Client should think about what they want out of the bridge inspection system and then focus on that. A large amount of inventory data is required, but it does not

	really provide any valuable information. Clients should determine what information is useful and not just use/perform what was done in the past. The remedial measures also take a long time to identify and assign to defects on site. This is considered a waste of time. One should consider what is important and remove all other information that just clogs up the system. The Client should always be current with the latest available technology and drive technologically advanced processes for industry to follow. For example, the Client can make the requirement for the next round of bridge inspection that all the inspectors must use handheld devices or drones to capture inventory.
9	Difficult to say. Site conditions such as dense vegetation plays a role. This is where the DRE offices can play a role in clearing the sites in advance of the inspections. Clients should also make available as much information as possible prior to the inspections. Consideration should be given to making available previous condition assessment results.
10	The client should allow bridge inspectors to use technology as required within the scope of works and requirements as this can increase the speed/accuracy of inspections. One can also easily identify spalling, concrete wearing, etc, by using drone footage.
11	The client can provide better software. A lot of time is wasted on using inefficient software. The method of calculating costs/fees was unnecessary complicated. Calibration of inspection teams by means of a workshop for the inspectors is required.
12	The client should provide more data on access, bush clearing should happen in advance of the inspections and free software training should be provided. The client should also ensure that the required software is in good working order.
13	The client should offer training as well as a calibration day for all inspectors. Accurate GPS locations of the structures should be provided to the consultant to improve the planning and efficiency. Consultants sometimes drive an entire day to just look for a structure and end up finding that there is no structure at the said location. A clear brief from the client is very important. TMH19 is perhaps too extensive, and it should be referred to only to extract the relevant information in terms of a client specific brief/scope of works.
14	Provide adequate time for the whole process, i.e., preparation beforehand, inspection time, capturing the data and then preparation of the data to be sent to the Client. Client can “force” the consultants to use UAV’s which will eliminate partial inspections. Using a UAV might aid with the excessive time it takes uploading of images. This might mean that you only have to upload a video. However, video footage is big, and this might result in alleviating the post processing time. I am not sure on this one.
15	Clients can assist in pre-identifying structures where access is limited/restricted and provide this information to the consultant in advance of the inspections. The client should likely have this information based on previous inspections.
16	Calibrating courses (2) Software/Hardware development for UAV’s, improved capturing software (3) Pre and post system efficiency

17	Clients should be open to integrated digital systems. Clients should be willing to update their systems to an integrated system. For example, client should consider a dashboard type of interface for managing bridges as well. The technology is out there and available. Clients should consider consultants to develop systems to fit their needs.
18	Have a well optimised BMS, have very clear guidelines and rules about what is expected and required from inspections, stay current with the ever-evolving technology in the field of inspections and engineering (and international trends), have an updated and accurate database of bridge stock and allow consultant to pilot projects during inspection to show more efficient methodologies and approaches to inspections.

Appendix G

G1: RPA flight performance information extract from AirData UAV

G2: Example of an approved Application for Private RPAS operations i.t.o. Civil Aviation Regulations, 2011 (CAR101.05.2)

G1: RPA flight performance information extract from AirData UAV

Metric / Imperial
Settings

Overview | Details | Equipment | Notifications | Large Map

Aug 19th, 2020 12:42PM Edit

GENERAL

POWER

SENSORS

CONTROLS

WEATHER

MEDIA

Aug 19th, 2020
12:42PM (+02:00)

Plane Name
Phantom 4 Pro

Flight Air Time
07m 33s

Takeoff Battery
98% 17.1v

Landing Battery
73% 15.9v

P4P/iOS
SDK App 4.11.2

Total Kilometrage
974 m

Max Distance
125 m

Max Altitude
81.7 m

Max Speed
9.71 m/s

Max Bat Temp
34.95°c

Tips: **1**
Warnings: **0**

Download: KML GPX (?) CSV Original

Metric / Imperial
Settings

Efficiency | Battery Cells | Cells Graph | Volts and Amps | Battery Info

GENERAL

POWER

SENSORS

CONTROLS

WEATHER

MEDIA

The following values are affected by multiple factors including pilot actions (flying style, altitude changes, etc) and environmental conditions (air temperature, winds, etc).

Consistent low values may indicate an issue with the Phantom, such as blade issues, motor issues or battery issues.

Longer flights will provide more accurate information.

Minutes Per Battery ™
Higher is better

Flight time
07m 33s

Total Mileage
974 m

Max Height
81.7 m

Kilometers Per Battery ™

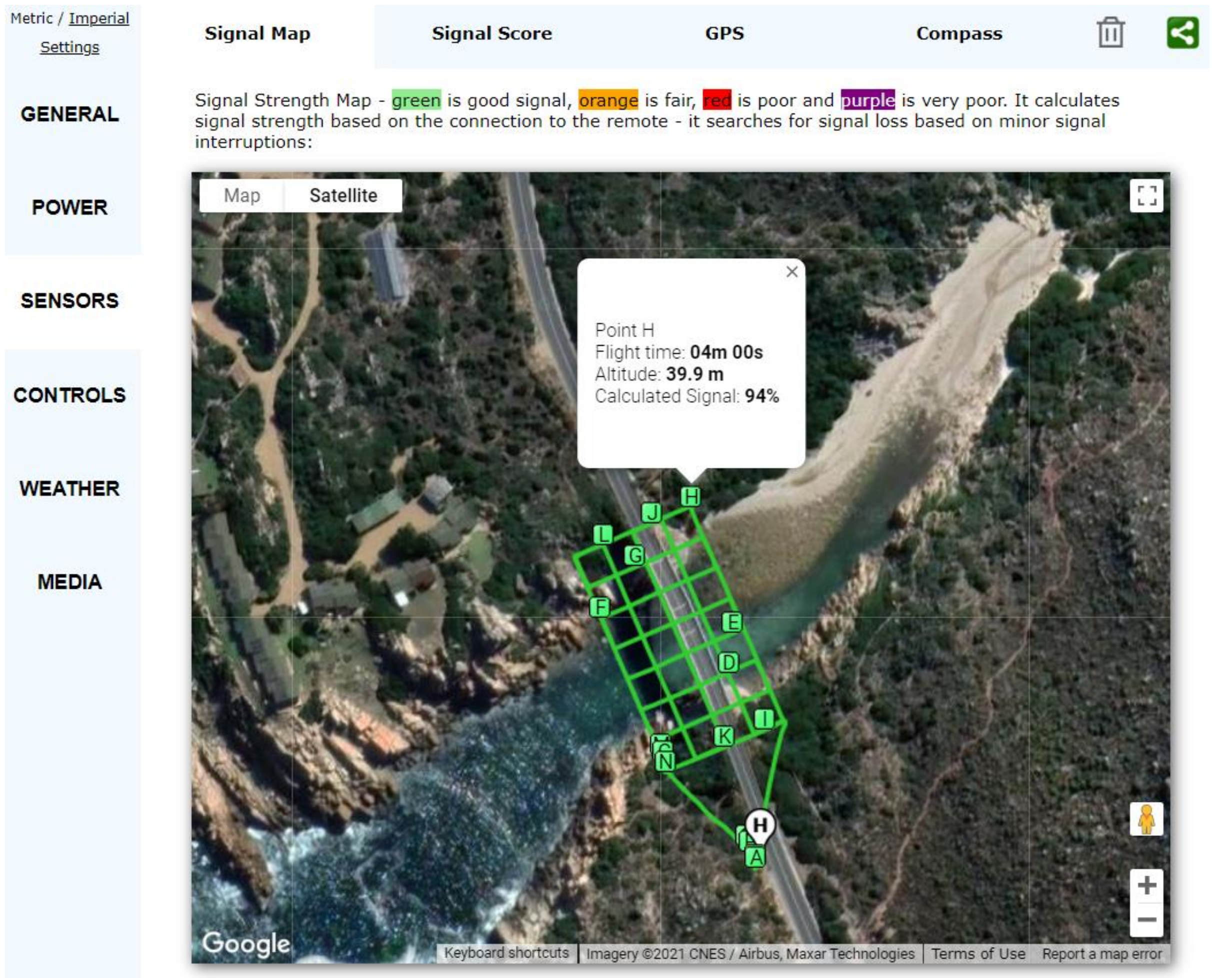
- **Minutes Per Battery:** how many minutes the aircraft can fly until the battery drains.
- **KM Per Battery:** how many kilometers (round trip) the aircraft can fly until the battery drains.

Explanation
Based on your average flying style this flight, these dials represent the time and distance you could have theoretically flown, assuming you continued flying in the same way until your battery was completely drained.

Minutes Per Battery - this number will be lower if you put the aircraft under stress, such as frequent ascends/descends, high wind, mechanical stress on the aircraft (propellers, motors, cracks), inefficient battery, etc.

Miles/KM per Battery - this number will vary significantly based on the flight characteristics. This dial is useful for comparisons of flights with similar distances. For example, if you take a short leisurely flight, this number will be lower as it assumes you will continue to travel slowly. If you fly far with very little stops, this number will be higher as it assumes you will continue flying in the same manner.

IMPORTANT: these values are strictly theoretical. Do **not** try to fly to the maximums!


Metric / Imperial
Settings
GENERAL
POWER
SENSORS
CONTROLS
WEATHER
MEDIA
Signal Map
Signal Score
GPS
Compass
Signal Strength Map - green is good signal, orange is fair, red is poor and purple is very poor. It calculates signal strength based on the connection to the remote - it searches for signal loss based on minor signal interruptions:
Map
Satellite
Point H
Flight time: 04m 00s
Altitude: 39.9 m
Calculated Signal: 94%
Google
Keyboard shortcuts
Imagery ©2021 CNES / Airbus, Maxar Technologies
Terms of Use
Report a map error

G2: Example of an approved Application for Private RPAS operations i.t.o. Civil Aviation Regulations, 2011 (CAR101.05.2)

CITY OF CAPE TOWN
ISIXEKO SASEKAPA
STAD KAAPSTAD

SAFETY AND SECURITY DIRECTORATE
DISASTER RISK MANAGEMENT CENTRE
[redacted]

Head: LOGISTICS PLANNING AND FLEET MANAGEMENT

[redacted]

APPLICATION FOR PRIVATE RPAS OPERATIONS I.TO. CIVIL AVIATION REGULATIONS, 2011 (CAR 101.05.2)

1.	**OPERATOR**			
	Name	Integrated Aerial Systems (Pty) Ltd	Licence Number	[redacted]
	Contact Person	[redacted]	**ROC Number:**	[redacted]
	E-mail Address	[redacted]	Tel	[redacted]
	Cell		Fax	N/A
2.	**DATE: (Of Operation)**	19/08/2020-23/08/2020	**Times:** From 10:00	Till 16:00
3.	RPAS Type & Class:	Muiltirotor Class 3B		
	RPAS Make & Model	DJI Phantom 4 Pro	Registration	[redacted]
4.	**REMOTE PILOT OPERATOR:**	Name	[redacted]	
		Licence Number	[redacted]	
5.	**FLIGHT DETAIL**			
	Private/Commercial	Commercial	No. of Landings	8
	Type of Flight	VLOS / E-VLOS / R-VLOS	ETA & ETD	10:00-16:00
6.	**LANDING AREA**			
6.1	Name of Premises/Location	Benning Bridge	Erf Number:	N/A
	Physical Address	Over Steenbras River on the R44		
	The pilot inspected	YES / NO	(If no: provide reason)	

6.2 Attached is a plan view drawing/photographs of the are indicating the following:
Location. Position in relation to buildings and structures. Size an any Telephone/high tension wires or any other obstructions within 50m of the area

7.	**FLIGHT PATH**				
7.1	Confirm that	The entry and exit paths are clear of obstructions		YES	NO
		The flight path will at all times be at least 50m. Laterally, away from any open-air assembly of people		YES	NO
8.	**THIRD PARTY INTEREST**				
8.1	Confirm that	Measures are in place for crowd control		YES	NO
		Written permission obtained from landowner/(s)		YES	NO

9. **DECLARATION**

I, [redacted] the undersigned, in my capacity is

Safety manager of Integrated Aerial Systems hereby confirm that the above- mentioned information

is true and correct. I make this application to the City of Cape Town, on the information supplied, in terms of Civil Aviation Regulations Part 91.07.4(2) of 1997 for the approval of this flight. I further confirm full compliance with all relevant, prescribed, provisions as set out in the Aviation Act, Act No. 74 of 1962, the Air Traffic Navigation Regulations of 1976, the Civil Aviation Regulations of 1991 and the Services Licensing Act, Act No. 115 of 1990, the Domestic Air Services Regulations of 1991 and the Operations Manual of "Integrated Aerial Systems (Pty) Ltd" for the duration of the Operation. (Operations Manual not applicable to private flights).

FOR OFFICE USE ONLY

APPROVAL OFFICER	DISASTER RISK MANAGEMENT	PAYMENT DETAILS		APROVAL STATUS
SIGNATURE	18 AUG 2020	ACCOUNT #	-	APPROVED
DATE	[redacted]	COST CENTRE	-	REJECTED 2020-08-18
PLACE	[redacted]	GL CODE	-	DISASTER RISK MANAGEMENT

APPROVED
THIS AVIATION PERMIT IS ONLY VALID WHEN

Kindly attached numbered annexes to this form for detailed explanations if necessary. Approval, when given, is done on the facts Submitted and the declaration made. THIS APPLICATION MUST BE SUBMITTED AT LEAST 72 HRS PRIOR TO THE FLIGHT

File Reference: [redacted]	Page 1 of 1

Visit us at http://www.capetown.gov.za/disaster / Fax: 086 576 2086 or
E-mail us on Aviation.Operations@capetown.gov.za or DisasterRiskManagement.Centre@capetown.gov.za

DISASTER HELP LINE:	080-911-HELP	080-911-4357
DISASTER INFORMATION LINE:	080-112-HELP	080-112-4357

GOODWOOD FIRE STATION LOKUCIMA UMLILO LASE I-GOODWOOD GOODWOOD BRANDWEERSTASIE
C/O FRANS CONRADIE & HUGO STREET GOODWOOD, CAPE TOWN 7460 PO BOX 298 CAPE TOWN 8000
www.capetown.gov.za/disaster

Making progress possible. Together.

Appendix H

Evaluation of inventory photograph quality

White Bridge																									
	Capturing device >	**RPA (DJI Mavi Mini)**												**Handheld Digital Camera**											
	Photogrpahs Nr. >	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**15**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**15**
Criteria	Composition	2	2	2	2	1	1	2	2	1	2	2	1	1	1	1	1	1	1	1	1	1	2	1	2
	Lighting	0	1	2	2	0	2	2	2	2	2	2	2	0	1	2	2	0	2	2	2	2	2	2	2
	Focus	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Overall impression	1	1	2	2	0	1	2	2	1	2	2	1	0	1	2	2	0	1	1	1	1	2	1	2
	Individual score	5	6	8	8	3	6	8	8	6	8	8	6	3	5	7	7	3	6	6	6	6	8	6	8
	Subset score	83%												74%											

Benning Bridge																									
	Capturing device >	**RPA (DJI Phantom 4 Pro)**												**Handheld Digital Camera**											
	Photogrpahs Nr. >	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**15**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**15**
Criteria	Composition	2	2	2	2	2	2	2	2	1	2	2	2	1	2	2	2	2	2	1	1	2	1	1	2
	Lighting	2	2	2	2	2	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2
	Focus	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Overall impression	2	2	2	2	2	2	2	2	1	2	2	2	1	2	2	2	1	1	1	1	2	1	1	2
	Individual score	8	8	8	8	8	8	8	8	6	8	8	8	5	8	8	8	7	7	6	6	8	6	6	8
	Subset score	98%												86%											

Description	**Score**
Good	2
Fair	1
Poor	0

Colour Legend
Better qaulity
Equal qaulity
Poorer qaulity

Appendix I

Draft TMH 22 condition categories of a structures

PCI – Priority condition index

Priority condition index is calculated by the StrumanBMS software using the degree, extent and relevancy ratings of the defects inputted for each inspection item. The PCI is used to identify those structures with critical defects that should receive urgent attention. The calculation of the PCI is described in an addendum to TMH22 - *Deduct Points Method Structures.* Note that the Structure Priority Condition Index (SPCI) from TMH22 is not used.

In short, the PCI is calculated by subtracting the weighted deduct points from the worst 5 defects. PCI ranges from 2.5, i.e., the worst condition, to 100, i.e., the best condition. If a structure has a PCI of 100, it means that there are no defects on the structure. The table below extracted from TMH22 gives the condition categories and index range values

Make safe and urgent repairs identified in inspection reports (adapted and developed by WCG DTPW Structure Design Division)

The PCI is strongly focused on identifying the worst and most heavily weighted structural defects and thus structures with hazardous of unsafe elements (such as guardrails, parapets, etc.) may not be identified by the PCI alone. To help identified these structures that may require attention and are not identified as urgent by the PCI value, the consultants completing the inspection were requested to report any unsafe (MS - Make safe) items and report on all structures require urgent attention (a minimum of the 5 worst structures was request per work package).

Table 3: Condition and functional categories (as defined in Table E1 in the Draft TMH22)

Condition Category	Index Range	Condition Category Description	Functional Category Description	Colour Code
Very Good	85 - 100	Asset is still like new and no problems are expected.	Good service levels at all times	Blue
Good	70 – 85	Asset is still in a condition that only requires routine maintenance to retain its condition.	Mostly good service levels with isolated problems occurring at certain times.	Green
Fair	50 – 70	Some clearly evident deterioration and would benefit from preventative maintenance or requires renewal of isolated areas.	Reasonable service but with intermittent poor service.	Orange
Poor	30 – 50	Asset needs significant renewal or rehabilitation to improve its structural integrity	Generally poor service levels with occasional very poor service being provided.	Red
Critical	0 - 30	Asset is in imminent danger of structural failure and requires substantial renewal or upgrading with less than 10% of EUL remaining.	Very poor service levels at most times.	Purple

Appendix J

COTO accreditation requirements

COTO TMH19 (draft) ACCREDITATION REQUIREMENTS FOR BRIDGE AND CULVERT INSPECTORS

The minimum experience and qualification are as follows:

Culvert Inspector

A qualified technician, technologist or engineer with an absolute minimum of 5 years bridge and culvert design experience obtained during the last 20 years. Structural design experience will also be considered.

In addition to the above experience and qualification, an applicant must have attended a two-day COTO Structures Subcommittee-accredited bridge and culvert inspector's course that covers the TMH19 DER methodology. The applicant must also have passed the associated exam. The required experience must have already been obtained before attending the course. Time spent on site does not qualify as design experience towards accreditation.

Bridge Inspector

Professional Engineers who have an absolute minimum of 5 years bridge and culvert design experience obtained during the last 20 years or Professional Technologists who have a minimum of 10 years bridge and culvert design experience obtained during the last 25 years. Experience put forward must be personal design experience and does not include signing off designs done by others. Managers in charge of structural design, who do not have the required years of personal design experience themselves, do not qualify.

In addition to the above experience and qualification an applicant must have attended a two-day COTO Structures Subcommittee-accredited bridge and culvert inspector's course that covers the TMH19 DER methodology. The applicant must also have passed the associated exam. The required experience must have already been obtained before attending the course. Time spent on site does not qualify as design experience towards accreditation. Those that have the required experience at time of course, but were not professionally registered, may apply for accreditation as soon as they have professionally registered. Applications in such cases should be received not later than 12 months of the course attendance. This time period allowed may be extended in special cases at the sole discretion of the COTO Structures Sub-committee accreditation evaluation committee.

Senior Bridge Inspector

Professional Engineers with a minimum of 15 years full time personal bridge design experience accumulated over their career. It is of utmost importance the applicant also has personal design experience in Continuous Prestressed Bridges as well extensive other experience. Ideally such a candidate will also be in a senior position involving the overseeing and advising of more junior bridge designers. As such, the candidate will have made bridges and the management of bridges their full time career and will be conversant with all aspects of the management of road structures from design through to construction, maintenance and repair. The design experience put forward must be personal experience and does not include merely signing off designs done by others. Managers in charge of design sections, who do not have the required years of personal design experience themselves, do not qualify.

Additional requirements for all inspector grades

In addition to the above experience and qualification, an applicant must have attended a two-day COTO Structures Subcommittee-accredited bridge and culvert inspector's course that covers the TMH19 DER methodology. The applicant must also have passed the associated exam. However it must be noted that the exam merely indicates that the candidate understands the TMH19 DER methodology of bridge and structure inspections and does not automatically qualify a candidate to be accredited. The required **design experience** as stated above, is a key requirement towards accreditation as an inspector. Even those who have a limited knowledge of structures are known to have managed to pass the exam but do not necessarily understand the intricacies of the various defects found on structures in the field. The professional responsibility of the inspector is paramount, as when failures occur, the inspection data often will form part of court cases. Thus candidates assume a serious responsibility should they be accredited and inspect structures on behalf of a client.

Appendix K

Ethics approval

UNIVERSITEIT
STELLENBOSCH
UNIVERSITY

NOTICE OF APPROVAL

REC: Social, Behavioural and Education Research (SBER) - Initial Application Form

13 November 2019

Project number: 11584

Project Title: An investigation into the feasibility of using commercially available small Unmanned Aerial Vehicles for bridge inspection activities

Dear Mr Johannes Neethling

Your REC: Social, Behavioural and Education Research (SBER) - Initial Application Form submitted on 11 November 2019 was reviewed and approved by the REC: Humanities.

Please note the following for your approved submission:

Ethics approval period:

Protocol approval date (Humanities)	Protocol expiration date (Humanities)
13 November 2019	12 November 2022

GENERAL COMMENTS:

The researcher is reminded to upload proof of permission once obtained from the Western Cape Government Department of Transport and Public Works. [ACTION REQUIRED]

Please take note of the General Investigator Responsibilities attached to this letter. You may commence with your research after complying fully with these guidelines.

If the researcher deviates in any way from the proposal approved by the REC: Humanities, the researcher must notify the REC of these changes.

Please use your SU project number (11584) on any documents or correspondence with the REC concerning your project.

Please note that the REC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

FOR CONTINUATION OF PROJECTS AFTER REC APPROVAL PERIOD

Please note that a progress report should be submitted to the Research Ethics Committee: Humanities before the approval period has expired if a continuation of ethics approval is required. The Committee will then consider the continuation of the project for a further year (if necessary)

Included Documents:

Document Type	File Name	Date	Version
Informed Consent Form	15094049 Template-1-Written-Consent	11/09/2019	1
Request for permission	15094049 Template-4-Application-Letter-for-Institutional-Permission	24/09/2019	1
Data collection tool	15094049 Interview Guide 11584	30/09/2019	1
Research Protocol/Proposal	15094049 Research Proposal 11584	06/10/2019	1
Informed Consent Form	15094049 Template-1-Written-Consent Rev1	20/10/2019	2
Data collection tool	15094049 Interview Guide 11584 rev2	20/10/2019	2
Data collection tool	15094049 Observation Sheet 11584 rev1	11/11/2019	1

Appendix L

L1: Completed draft safety inspection evaluation sheet using the photo-realistic 3D model

L2: Completed inventory inspection sheet using the photo-realistic 3D model

L3: StrumanBMS inspection sheet

L1: Completed draft Safety Inspection Evaluation Sheet using the photo-realistic 3D model

Western Cape Government Transport and Public Works	SAFETY INSPECTION FORM i.t.o. Occupational Health and Safety Act (1993) and Construction Regulations (2014)	BRIDGES

Route	TR02701	Section	R44	Road km	53.1
Structure No.	B2604	Latitude	-34.193669	Longitude	18.821078
No of Spans	1				
Structure Name	Steenbars River Arch Bridge (Benning Bridge)				

The purpose of this Safety Inspection, to be undertaken by a competent person, is to identify **safety related defects** that require **urgent attention to ensure the structure is safe for continued use**. It is not required to record routine maintenance defects. **If Urgent action is required the inspector should not leave site until authorities have alerted to implement appropriate safety measures.** These inspections are to be captured and hard copy and electronic records kept. Data shall be captured in StrumanBMS system (in future). For existing structures inspections shall at 12 months maximum intervals. For new structures they shall be done every 6 months for the first 24 months and at 12 months maximum intervals thereafter

INSPECTION (mark with an X as applicable for Defect, Degree and Urgent action)

Item	Description	Defect?			If Yes Degree Rating				Urgent action req.
		Yes	No	N/A	1	2	3	4	Tick if relevant
1	Upper approaches (incl. guardrails)		X						
2	Abutments (incl. retaining walls)		X						
3	Piers	X			X				
4	Top of deck	X			X				
5	Underside of deck	X			X				
6	Handrails/parapets (incl. sidewalks)	X				X			
7	Expansion joints	X				X			
8	Flood damage?		X						
9	Impact damage?		X						
10	Other defects?		X						

PHOTOGRAPHS

Photo No.	Inventory Description	Photo No.	Item	Defect Description
P01	Upper approach showing parapets	UA01		
P02	Bridge elevation	UA02		
P03	Underside of deck	UA03		
P04	Bridge number	UA04		
P05		UA05		
P06		UA06		
P07		UA07		
P08		UA08		
P09		UA09		
P10		UA10		

Urgent Action or Attention required?	Yes		No	X	No Access		Access issues	
If Yes, specify details:								

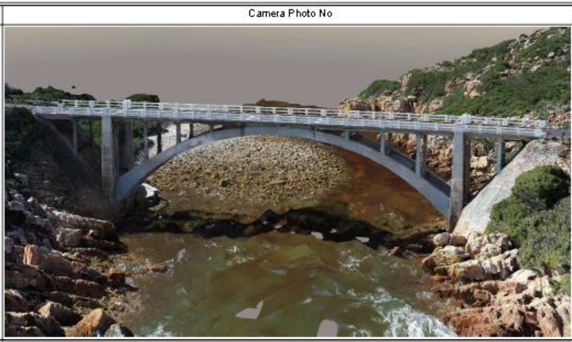
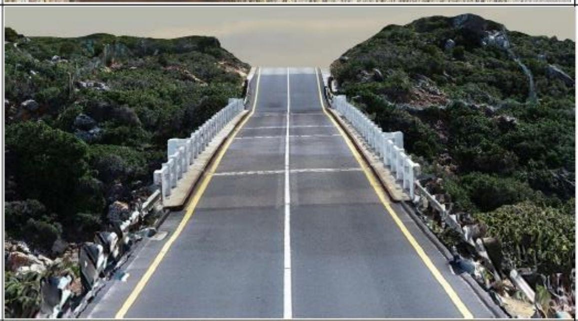
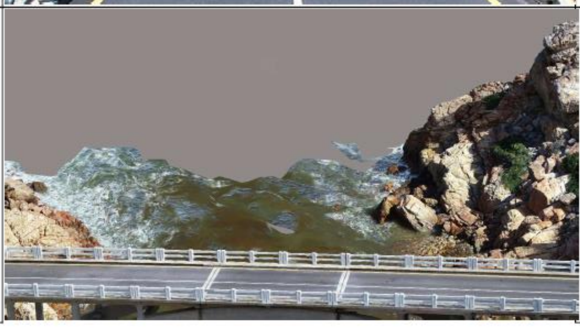
Inspector's comments: Large arch bridge reviewed for saftey using photogrammetery model. Structure in good condition, hard to identified small cracks or spall using virtual model, some areas like approaches and underside of deck not very detailed.

Inspected by	Wessel Lourens	Date	2021-06-09
Signature		Firm	WCG - DTPW

Degree Rating Description	No Defect	0	Minor	1	Moderate	2	Warning	3	Severe	4

L2: StrumanBMS Inspection Sheet

ROAD AUTHORITY	STRUCTURE TYPE	STRUCTURE NUMBER	
Western Cape Government Transport and Public Works	BRIDGE	B2604	CSIR STRUMAN SYSTEM
		STRUCTURE NAME	
		Benning Bridge	
INFORMATION			INVENTORY PHOTO RECORD SHEET
Inspector Name	Consultant firm	Date (dd/mm/yyyy)	
Johannes Neethling	WCG	25/01/2021	

Photo No	Description		Camera Photo No	Optional Comments
V01	View 1	Bridge in Elevation *Must show total length of bridge, full pier heights and abutments. If necessary take several photos and combine electronically. For multi-level interchanges more than one bridge may be in photo. Please identify bridge and also describe other bridges in the photo*		
V02	View 2	Bridge in Elevation from opposite side *Two separate closely spaced bridges may require a different elevation photo; either from the top of the other bridge showing the balustrades otherwise a skew elevation from gap between the two bridges*		
V03	View 3	Bridge from upper approach *In the direction of the increasing chainage of the road - full bridge must be show along road centreline*		
V04	View 4	Bridge from upper approach opposite end *In the direction of the decreasing chainage of the road - full bridge must be show along road centreline*		
V05	View 5	View taken from the top of the bridge of feature crossed *Road, rail or upstream river view*		

V06	View 6	View taken from the top of the bridge of feature crossed opposite end *Road, rail or downstream river view*		
V07	View 7	Deck edge to show profile of deck cantilever soffit *Not top of parapet – must see outside edge of deck*		
V08	View 8	Opposite deck edge to show profile of deck cantilever soffit *Not top of parapet – must see outside edge of deck*		
V09	View 9	Underside of deck *Take photo of each type*		
V10	View 10	Typical pier *Take photo of each type*		

V11	View 11	Typical Abutment Take photo of each type		
V12	View 12	Bridge number on endblock *If there is no number take a photo of endblock where it should have been*		
V13	View 13	Other bridge number adjacent to other road or rail.		
V14	View 14	Typical parapet elevation *Take photo of each type*		
V15	View 15	Typical roadway joint *Take photo of each type*		

L3: StrumanBMS Inspection Sheet

STRUMAN Bridge and Structure Management System

Inspection Sheet - Structure: B2604 - STEENBRAS RIVER (BENNING BRIDGE)

Inspection Sheet_TMH19

Road Autority	Structure Type	Structure Number	Structure Name
Provincial Government Western Cape	**Bridge - Arch**	B2604	STEENBRAS RIVER (BENNING BRIDGE)

Inspection Information

Inspection Type	Inspector Name	Firm	Date
Principal	P RONNE	AECOM	2019/11/13 00:00:00

GIS Coordinates Y (m)	GIS Coordinates X (m)	GPS Coordinates Latitude	GPS Coordinates Longitude
34.193669	18.821078	34.193669	18.821078

Vertical Clearances

Position/Span No				
Minimum Height (m)				

Location Details

Road Number	Road km	DRE_Area	District Municipality	Suburb
TR02701	53.1	Paarl	City of Cape Town (DMC)	City of Cape Town (LMB)

Structure Information

No of spans	Bridge orientation	Overall length	Angle of skew	Year constructed	Bridge Type
5	North/South	65.06	90	1933	Arch

Inspection Ratings

General Items

Item	Position	D	E	R
01. Approach Embankment	A1	0	-	-
01. Approach Embankment	A2	0	-	-
02. Guardrail		0	-	-
03. Waterway		0	-	-
04. Approach Embankment Protection Works	A1	0	-	-
04. Approach Embankment Protection Works	A2	0	-	-
05. Abutment Foundations	A1	0	-	-
05. Abutment Foundations	A2	0	-	-
06. Abutments	A1	1	1	1
06. Abutments	A2	1	1	1
07. Wing/Retaining Walls	A1	X	-	-
07. Wing/Retaining Walls	A2	X	-	-
08. Surfacing		0	-	-
09. Superstructure Drainage		0	-	-
10. Kerbs / Sidewalks		0	-	-
11. Parapet		2	2	2
21. Miscellaneous Items		X	-	-

Pier Items

12. Pier Protection Works D	E	R	13. Pier Foundations D	E	R	14. Piers & Columns D	E	R

Other Support Items

	15. Bearings D	E	R	16. Support Drainage D	E	R	17. Expansion Joints D	E	R
A1	0	-	-	0	-	-	0	-	-
A2	0	-	-	0	-	-	0	-	-

Span Items

	18. Longitudinal Members D	E	R	19. Transverse Members D	E	R	20. Decks and Slabs D	E	R
S1	0	-	-	2	2	2	0	-	-
S2	2	2	2	0	-	-	1	1	1
S3	2	2	2	2	2	3	1	1	1
S4	2	2	2	2	2	3	1	1	1
S5	0	-	-	0	-	-	0	-	-

Remedial Work

	Inspection Item	Position	Activity	Qty	Unit	Urg	MS	Remarks	MF	Photos
1	18. Longitudinal Members	AS	18.118. Repair spall (including honeycombing)	25	L	3	N			S01
2	18. Longitudinal Members	S3	18.118. Repair spall (including honeycombing)	250	L	2	N			S03
3	18. Longitudinal Members	AS	18.118. Repair spall (including honeycombing)	1	L	3	N			S02
4	20. Decks and Slabs	S3	20.953. Ad-hoc item (describe under Remarks)	1	No	2	N	REMOVE FORMWORK		S04
5	19. Transverse Members	S4	19.118. Repair spall (including honeycombing)	20	L	2	N			S05
6	18. Longitudinal Members	AS	18.118. Repair spall (including honeycombing)	20	L	3	N			S06
7	18. Longitudinal Members	AS	18.118. Repair spall (including honeycombing)	10	L	3	N			S07
8	18. Longitudinal Members	S5	18.118. Repair spall (including honeycombing)	10	L	3	N			S08
9	18. Longitudinal Members	S5	18.118. Repair spall (including honeycombing)	250	L	3	N			S09
10	11. Parapet	AS	11.118. Repair spall (including honeycombing)	50	L	3	N			S10
11	19. Transverse Members	S1	19.118. Repair spall (including honeycombing)	350	L	3	N			S11
12	18. Longitudinal Members	S1	18.118. Repair spall (including honeycombing)	50	L	3	N			S12

Inspector's assessment of structure condition and further comments		
Inspector's Comments	MODERATE CONDITION (RECENTLY REHABILITATED). REPAIR STRATEGY IMPLEMENTED AT SPRING POINTS MASKS ACTIVE CORROSION SITES - NOW UNINSPECTABLE.	
Further inspection needed ?	N	**If further inspection required, indicate special requirements:**
UBIU used ?	N	NO
UBIU needed ?	N	

D -DEGREE							E - EXTENT				R - RELEVANCY				U - URGENCY					
NA	UA Insp	None	Minor	Fair	Poor	Severe	Local	>Local	<Gnl	General	Min	Moderate	Major	Critical	Record	Monitor	Routine	<5 yrs	<2 yrs	ASAP
X	U	0	1	2	3	4	1	2	3	4	1	2	3	4	R	0	1	2	3	4