Structural Monitoring and Maintenance, *Vol. 2, No. 3 (2015) 283-300*
DOI: http://dx.doi.org/10.12989/smm.2015.2.3.283

Towards UAV-based bridge inspection systems: a review and an application perspective

Brodie Chan[1,2a], Hong Guan[*1], Jun Jo[3b] and Michael Blumenstein[3c]

[1]*Griffith School of Engineering, Griffith University Gold Coast Campus, QLD 4222, Australia*
[2]*GHD Pty Ltd, Brisbane 4000, QLD, Australia*
[3]*School of Information and Communication Technology, Griffith University Gold Coast Campus, QLD 4222, Australia*

(Received March 9, 2015, Revised August 17, 2015, Accepted August 25, 2015)

Abstract. Visual condition inspections remain paramount to assessing the current deterioration status of a bridge and assigning remediation or maintenance tasks so as to ensure the ongoing serviceability of the structure. However, in recent years, there has been an increasing backlog of maintenance activities. Existing research reveals that this is attributable to the labour-intensive, subjective and disruptive nature of the current bridge inspection method. Current processes ultimately require lane closures, traffic guidance schemes and inspection equipment. This not only increases the whole-of-life costs of the bridge, but also increases the risk to the travelling public as issues affecting the structural integrity may go unaddressed. As a tool for bridge condition inspections, Unmanned Aerial Vehicles (UAVs) or, drones, offer considerable potential, allowing a bridge to be visually assessed without the need for inspectors to walk across the deck or utilise under-bridge inspection units. With current inspection processes placing additional strain on the existing bridge maintenance resources, the technology has the potential to significantly reduce the overall inspection costs and disruption caused to the travelling public. In addition to this, the use of automated aerial image capture enables engineers to better understand a situation through the 3D spatial context offered by UAV systems. However, the use of UAV for bridge inspection involves a number of critical issues to be resolved, including stability and accuracy of control, and safety to people. SLAM (Simultaneous Localisation and Mapping) is a technique that could be used by a UAV to build a map of the bridge underneath, while simultaneously determining its location on the constructed map. While there are considerable economic and risk-related benefits created through introducing entirely new ways of inspecting bridges and visualising information, there also remain hindrances to the wider deployment of UAVs. This study is to provide a context for use of UAVs for conducting visual bridge inspections, in addition to addressing the obstacles that are required to be overcome in order for the technology to be integrated into current practice.

Keywords: unmanned aerial vehicle; bridge inspection; condition assessment; bridge asset management

---

∗Corresponding author, Associate Professor, E-mail: h.guan@griffith.edu.au
[a] BEng, E-mail: brodie.chan@hotmail.com
[b] Ph.D., E-mail: j.jo@griffith.edu.au
[c] Ph.D., E-mail: m.blumenstein@griffith.edu.au

http://www.techno-press.org/?journal=smm&subpage=7 ISSN: 2288-6605 (Print), 2288-6613 (Online)

1. Introduction

As is the case for all load bearing transport structures, the deterioration of a bridge is a function of time, the nature of the environment, load capacity, construction procedures, load frequency and quantum. The uncertainty of these variables often influences the actual rate at which deterioration occurs, requiring regular inspections to accurately assess the current condition state of a structure. To ensure the ongoing serviceability and safety to the travelling public, it is essential that data relating to the bridge deterioration and the condition of individual components be recorded. An analysis of this data enables deterioration mechanisms and patterns to be identified and hence, maintenance or remediation works to be assigned.

With the number of ageing structures in the inventory of asset owners and government authorities combined with the existing constraints on resources, there has been an increasing demand placed on maintenance services over the past decade. In Queensland, Australia alone, this equates to over 3,000 road bridges and in excess of 10,000 culvert bridges with a net replacement value of over $2 billion (Department of Transport and Main Roads (DTMR), 2002). However, the current approach to bridge maintenance is both inefficient in how inspections are conducted and relevant information is collected.

Traditionally, bridge inspections are conducted manually through traffic control and traditional bridge access methods, which include under-bridge inspection units, mobile scaffolding, boom lifts and cherry pickers. Whilst this approach to bridge condition assessments allows inspectors to get up close to the structure, a considerable amount of time and resources are consumed. Given the scarcity of resources and qualified inspectors, this has ultimately led to a backlog of maintenance activities, creating the potential for defects affecting the structural integrity of a bridge to go unnoticed.

One of the key issues with the current manual approach to bridge condition inspections is the Bridge Information Systems (BIS) that are required to support the approach. These systems are essentially databases, where data relating to the current condition of each component, along with any defects, is recorded. This offers limited interpretability and prevent engineers that have no previous knowledge of the structure, from being able to accurately visualise “what the data means”. This results in inadequate assessments of the overall condition, which increases the risk of failure and whole-of-life costs for a structure. By introducing a more efficient approach to bridge inspections, the efficiency of the current Bridge Management Systems (BMSs) can be improved.

Recent advances in flight technology and flight control capabilities, coupled with the significant reductions in cost have prompted the development of UAVs for monitoring applications, and more recently for the inspection of infrastructure (Adams *et al*. 2013). UAVs offer significant potential for bridge condition assessments, allowing users to collect aerial-based images from a UAV-mounted camera system. These aerial-based systems enable inspectors to overcome constraints imposed by ground-based inspection processes and have the potential to fill the void in current BMSs.

2. Historical platform development

Introduced in World War 1 and 2 was the initial concept of an unmanned aircraft, which was used for aerial assaults and gaining military intelligence through spy surveillance. With extensive research between 1960 and 1980, the concept of a UAV was produced. Since then, the development of UAV systems is no longer motivated by military goals and applications, rather infrastructure management applications. This includes traffic monitoring, construction engineering safety inspections and 3-D photogrammetric modelling (Irizarry *et al.* 2012). A study conducted by Srinivasan, et al. (2004) investigated the feasibility of an Airborne Traffic Surveilance System for the collection of data relating to traffic congestion and routes. Although the technology has seen unprecedented advancements, resulting in significant research into the feasibility of introducing UAVs for traffic and transport applications, the use of the technology for bridge condition assessment and maintenance has fallen behind.

As the name suggests, the UAV differs from traditional technologies as the drone aircraft is controlled autonomously, or under the remote control of a pilot. The most commonly utilised system is the multicopter, which consists of four or more brushless motors. What separates the UAV or drone from other technologies developed is the vertical capabilities, which enable it to take-off and land vertically, enabling operation in confined spaces (Puri 2005). With advancements in Inertial Measurement Units (IMU), Global Positioning Systems (GPS) and micro-processing units, current UAV technology offers high manoeuvrability and autonomous navigation, presenting limitless potential (Siebert and Teizer 2014).

During routine bridge condition inspections, local measurements and close-up images of bridge components and their relative damage is recorded. For bridge inspections, as shown in Fig. 1, the basic function of unmanned aerial vehicles is the capturing of this aerial imagery from digital cameras being mounted to the UAV (Siebert and Teizer 2014). This imagery of the entire structure enables inspections to be conducted and analysed, whilst providing temporal context. Although digital imagery has allowed engineers to capture numerous images with relative ease, it has failed to address the issue of adding context to the situation and has been noted to ‘overload’ engineers with information (Lattanzi and Miller 2013). Historically, there has been limited use of UAVs in condition state monitoring applications, such as bridge condition inspections. However, with the -advancements of digital and remote sensing platforms, image processing, and computational analysis capabilities, the potential of introducing UAVs for the purpose of bridge asset management (Heintz *et al.* 2007) has been recognised. With this in mind, the use of automated aerial image capturing presents the capability of enabling engineers to better understand a situation through the 3D special context offered by UAV systems (Lattanzi and Miller 2013, Puri 2005).

Fig. 1 Unmanned Aerial Vehicle (UAV) for visual inspection (Aibotix GmbH, 2014)

3. Comparative capabilities of aerial based inspections

With the development of the UAV technology, which has witnessed the inclusion of the IMU, GPS, magnetic compass and other navigational technology, there has been an increased capacity to conduct bridge condition inspections. What this has led to, is the reduced risk to inspectors, by removing the necessity to come within a close proximity to the structure and manually inspect the individual components, thereby enabling automation of the inspection process. As far as the risk is concerned, where bridge access requires lane closures and traffic control measures, fatalities have been recorded, which are to be attributed towards driver inattentiveness, failure to yield right-of-way, insufficient space between vehicles and unsafe travel speeds. In North America, there were in excess of 600 fatalities recorded in 2012, which were due to motor vehicle crashes in work zones (The National Work Zone Safety Information Clearinghouse, 2013). Through the introduction and integration of UAVs into bridge inspection processes, there is the potential to significantly reduce the risk to inspectors and other workers.

Typically, the adoption of autonomous technology for bridge inspections has been hindered by the inability to accurately assess the deterioration of critical components, such as bearings and joints from digital images taken by UAVs. However, the advancement in both the quality of photography and stability of autonomous aerial vehicle technology has made it possible to accurately assess these components, as illustrated in Fig. 2. From these images collected from a UAV-based inspection, it is perceivable that the roller bearings and mortar pads are in a sound condition with no signs of cracking in the pad or significant deterioration to the bearings. The quality of the imagery highlights the propensity of the technology to be used for condition inspections in accordance with regulatory requirements, whilst reducing the need for inspectors to manually get up close with the individual bridge components.

It is also widely recognised that reducing the dependence upon lane closures to conduct condition assessments on and individual-element basis carries tangible benefits for a project (Hachem *et al.* 1991). Highlighted as the most significant cost to bridge maintenance is the expenditure required for the utilisation of traffic control, which includes personnel and vehicles (Kamya 2010). Hence, the potential savings from the implementation of an aerial-based inspection system for the under-bridge components are perpetuated by reductions in traffic control hours. In a study conducted by the Highway IDEA Project 56 (Choset 2000), it was estimated that the combined cost of traffic control and access units consume 40-50% of the budget. Furthering this, it was estimated that the establishment and mobilisation of inspection-units accounts for 40-50% of the overall time required. UAVs are capable of optimising the inspection process, allowing for significant reductions in the time required for establishment and the cost of equipment and units, which ultimately benefits the project lifecycle.

4. Minimum requirements for bridge inspections

To be applicable for bridge condition state inspections, careful consideration should be given to the operational complexity of the UAV system. The overall goal of any new development is to either reduce the costs to the user, or the time required. In the case of UAV deployment for bridge inspections, two key factors are considered crucial, as outlined below.

Fig. 2 Inspection of bridge roller bearings (Aibotix GmbH, 2014)

4.1 Flexible platforms

It is important that the platform is flexible, allowing other technology to be easily integrated into the existing platform. Given the drive to introduce a more efficient system, a concept that remains possible through UAV-based condition inspections is the integration between aerial laser scanning and BIM software such as TEKLA Structures. Although image processing through UAV image acquisition has been limited in use, early studies by (Wang *et al*. 2004), which were later supported by Neitzel and Klonowski (2011), present the viability of using low-cost UAV systems for the mapping of structures such as buildings and bridges. Highlighted in Fig. 2 is the reconstruction of a structure from image processing point cloud data.

This technology enables the build-up of a historical database through developing profiles of structures, which can be used to enable more accurate assessments of the deflection of individual elements over the life of the structure. While this concept is still in the primitive stages of development, it provides rational for developing flexible UAV platforms that can be integrated with prospective technologies.

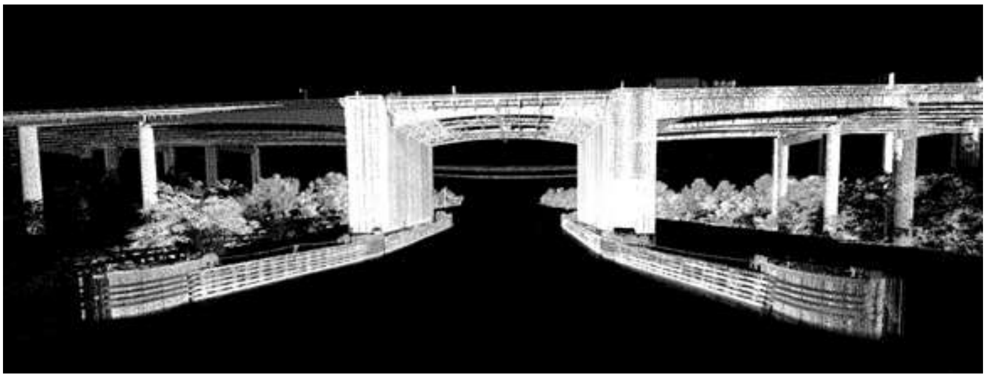


Fig. 3 3D Reconstruction of Louisiana I-10 Bridge (RIEGL Laser Measurement Systems GmbH, 2014)

4.2 Cost effectiveness

Recently, UAVs have been presented as a solution for a range of aerial-imaging applications, some of which include disaster management and traffic surveillance. UAVs are considered to be an inexpensive solution when compared with traditional manned operations, requiring lower operational and long-term maintenance costs. To be applicable to bridge condition inspections, the same is necessary, where the platforms achieve greater cost-efficiency relative to current processes.

With the advancements in technology, simple platforms consisting of small-scale drones with digital imaging equipment can be purchased for amounts that range between hundreds of dollars to ten thousand. Often operating on electric motors, these systems offer little maintenance and operational costs, ensuring greater cost efficiency over alternative robotic inspection methods (Advanced Highway Maintenance and Construction Program 2008, Oh *et al*. 2009). Adams *et al*. (2013) indicated that a UAV system consisting of a multicopter, sensors, ground control station and camera was assembled for less than $6000, being used for surveillance and monitoring. The initial expenditure may be a nontrivial amount. However, it will bring a long-term payoff, as this equipment will be reused for many bridges over a long period, with a low maintenance cost. The UAV components can be easily purchased from the Internet and assembled without any high-level skills.

5. Case study – cost-benefit analysis

Implementation of an aerial system has been associated with reducing the labour and resource costs, in addition to the Level of Service (LOS), which are incurred through temporary lane closures. To quantify the economic and social benefits of implementing a UAV-based inspection system for bridge condition assessments, an evaluation of the potential economic feasibility is presented herein, given the use on a typical two-span deck-unit bridge.

5.1 Bridge condition inspection

The structure inspected was a two-span deck unit bridge (see Fig. 4) in Queensland. This structure consisted of two lanes, one in each direction, with no room on the shoulder, preventing traffic from simply being diverted around the work zone without occupying a lane for the inspection. Consequently, a Traffic Management Plan (TMP) was required to describe the direction of traffic such that it ensures safety to road users and bridge inspectors. In order to conduct the inspection of the superstructure and substructure components, an under-bridge inspection unit was required, resulting in one of the lanes being occupied at all times.

Traffic control was utilised for the condition inspection for a total of 3.5 hours. From this, the inspection of the substructure and superstructure components amounted to 2 hours. This time is to be attributed to the mobilisation of the under-bridge unit, adjustments to traffic control layout and direction, and the assessment of the substructure and superstructure components.

5.2 Cost of resource utilisation

For the purpose of this case study, the visual inspection of the under-bridge components is more critical as it required an under-bridge inspection unit, and hence the closure of a single bridge lane. To enable the lane to be safely closed in accordance with the Department of Transport and Main Roads, a traffic guidance scheme was developed, detailing the use of traffic controllers with stop/go control.

Given the propensity for bridge substructure and superstructure components to be inspected by means of an unmanned aerial vehicle, a basic calculation of the potential resource benefits can be quantified through estimating the total amount of the budget spent on inspecting these components by traditional means. The cost for the hiring of traffic control is at the rate of $160 per hour. With 2 out of the 4 hours required for the inspection of substructure and superstructure components, the relative cost of traffic control would be $320.

For bridge access, the resources utilised included an under-bridge inspection unit and operator. While the estimated duration for under-bridge components is 2 hours, the minimum duration permissible for under-bridge inspection unit hire is 8 hours. Given that the standard rate for hire is $250 per hour, this equates to $2000. From summating these labour and resource expenses, the total budget allocated to the inspection of these substructure and superstructure components is approximately $2320.

Given that the bridge allows for observation from the batters and area directly beneath the deck unit, a UAV could be used for the inspection of these components. This freedom to move underneath the bridge structure reduces any issues with visual line of sight (VLOS) or programming and technology required for collision detection. As a result, these inspection unit and traffic control costs incurred for the inspection of under-bridge components could be eliminated.

It was previously identified in Section 2 that the initial investment required for a semi-permanent UAV system and associated image-capturing equipment was estimated to be $6000. With over $2000 spent in a single inspection for components that could have been assessed using a UAV, this highlights significant potential for the integration of UAVs into current bridge inspection processes.

Fig. 4 A Two-span two-lane deck unit bridge

5.3 Level of Service (LOS)

Although traffic management plans are devised to reduce the inconvenience caused to the travelling public and road users, traffic delays remain an inherent issue with traditional means of bridge inspection (Koonce *et al.* 2011). Given the scarcity of maintenance resources and availability of trained personnel, inspections are often scheduled in short time windows or intervals, preventing any major congestion from occurring. However, if work is not concluded within this allocated time-slot, significant costs and social disruptions may occur.

Given the potential socioeconomic issues that can arise through insufficient traffic planning and lane closures in critical road links, it is important to evaluate the LOS, which is a function of traffic delays. In accordance with the specifications of the Department of Transport and Main Roads (2014), the required length of the traffic control zone from the initial advance speed signage to the end of roadwork signage, is approximately 1.15 km. In addition to this, the length of the work area is 60 m, the approximate length of the bridge. To perform this analysis for the case described, the following information was acquired from a Road Impact Assessment:

- Annual average daily traffic = 1,022 (two-way demand)
- Peak hour traffic = 153 (two-way demand)
- % of heavy vehicles = 13%
- Base free flow speed = 100 km/hr

To underpin this data, the following assumptions were made, relating to the usage parameters and factors based on the stipulations of Hubner and Barton (2003):

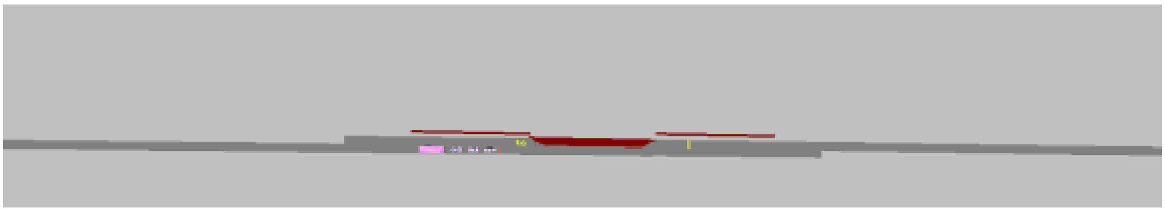
- Directional split = 70/30
- Peak hour factor = 90%
- Recreational demand = 80%
- Analysis period = 60 minutes
- Traffic cycle time = 180 seconds
- Work zone speed = 40 km/hr

From these variables, it was assessed that the approximate clearance time between which one lane is stopped and the next is allowed to progress, is estimated to be 10 seconds. To perform the analysis to quantify the overall delay to road users, the PTV Visum software (2013) was used. Using the information quantified above, an idealised situation is developed in the software, where the flow conditions and work zone characteristics are input. It is important to note here that the assessment period occurs after peak hour in the morning, where 70% of the traffic flow is heading in the east-bound direction. A visual illustration, as output from PTV Visum, is shown in Figure 4. The red zone in Figs. 5(a) and 5(b) illustrates the designated work zone, with the red lines representing the cumulative length of the zone under the authority of traffic control. These figures demonstrate the work zone and the redirection required to switch traffic heading west-bound, to the opposite lane through the work area. These images additionally represent the stop/go traffic condition that is created by the single lane closure.

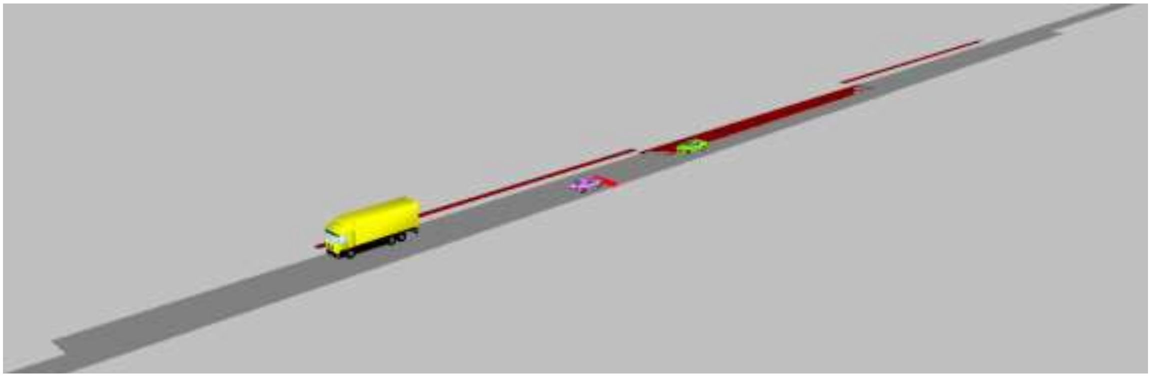
Shown in Table 1 is the estimated road-user delay output from the Visum software. This information highlights the significant cumulative delay which can be gauged as a function of the LOS. These levels are defined by the Transport Research Board (2000) and accepted by the Austroads standards (Hubner and Barton 2003), which are summarised in Table 2. LOS is a unit of measure that is defined by stages that represent the thresholds. These individual thresholds are defined by the parameters of driver discomfort, frustration, fuel consumption and increased travel time. At higher levels, cycle failure occurs, where the green phase does not enable the traffic to clear, leading to queued vehicles and traffic overflows.

An interpretation of Table 2 and extrapolating it to the data collected illustrate that while the traffic delays remain acceptable, there still remains significant delays to the individual road users. The most significant case created by this inspection occurs when the traffic control is switched to the western carriage way, creating an LOS of level C for the east-bound traffic. This signifies the moderate levels of driver discomfort, frustration and fuel consumption, which is perpetuated by the unexpected waiting times, and moderate cycle times.

While the structure inspected is not considered to be highly-trafficable, there are still significant delays caused. This traffic analysis highlights the potential benefits to road-users who may realise through adopting an alternative approach that replaces traditionally disruptive bridge inspection methods.



(a) Plan View



(b) Isometric View

Fig. 5 PTV Visum modelling output

Table 1 PTV Visum traffic delay output

	Delay (sec/vehicle)	Vehicles per hour	Cumulative Road-User Delay (sec/hr)	Level of Service
West-bound	19.5	60	1170	B
East-bound	33.7	65	2190.5	C

Table 2 Level of service (adapted from Transport Research Board, 2000)

Level	Description	Max Delay (sec/vehicle)
A	Low control delay, where vehicles generally arrive and progress when there is a green phase. Hence, most vehicles do not stop, or the short cycle lengths create minimal delays.	10
B	Occurs where there is good progression or short cycle lengths, leading to slightly higher levels of delay.	20
C	Progression is only fair, with longer cycle lengths and the potential for cycle failures.	35
D	Longer delays occur as the influence of unfavourable progression and cycle length, leading to higher vehicle per cycle ratios.	55
E	Indicative of poor progression, longer cycle lengths and high vehicle per cycle ratios.	80
F	Considered unacceptable, as oversaturation occurs and arrival flow exceeds lane capacity. May have many cycle failures.	> 80

5.4 Inspection duration

While costs are often attributed to the resources and labour required to conduct visual inspections, there are also costs associated with time utilised for inspections. With the shortage of inspectors who possess the necessary training and accreditation, and the increasing backlog of maintenance activities, reducing the time required for inspections becomes a key objective. As highlighted by Choset (2000), mobilisation and manoeuvring of traffic control and inspection units account for 40-50% of the overall inspection duration. To estimate the time that could be saved through utilising UAVs, some initial assumptions must be made. These are as follows:

- Mobilisation and manoeuvring of traffic control and inspection units account for exactly 50% of overall inspection duration.
- Of this 50%, the time allocated to traffic control mobilisation is 25% and to inspection unit manoeuvring is 25%.
- Of the 25% of the time that is allocated to mobilising traffic control and adjusting the lane closure, half of this is for the set-up associated with inspecting under-bridge components.

Based on these assumptions, it can be calculated that 37.5% of the overall inspection duration for the structure is attributed to the set-up and manoeuvring associated with inspecting under-bridge components. Hence for this particular bridge condition inspection, this accounts for 1.5 hours that may be saved by bridge inspectors. Under the Department of Transport and Main Roads bridge inspection requirements, two inspectors are required. Assuming a rate of $150 per hour, per inspector, this accumulates to a total of $450 that may be saved through utilising a UAV.

As a result, it can be concluded that through introducing a UAV, a significant amount of time can be saved by inspectors in these inspections. Ultimately, the time saved during the inspections may facilitate in the reduction of maintenance backlog and allow for more thorough inspections and assessments of component condition states.

5.5 Outcomes of case study

This analysis presents an idealised case encountered in which an aerial-based approach to bridge inspections may be used with quantifiable advantages. With over $2000 of the project budget simply attributed towards mobilising traffic control and the resources required for the inspection of substructure and superstructure components, there is significant justification for a UAV inspection system. From Table 3, it is presented the basic cost breakdown based on the necessity of traffic control and under bridge inspection units for manual inspections. This evaluation does not take into account the financial savings to be accorded to the project through reducing the time required for planning prior to mobilising to site.

In addition to this, the quantitative benefit to road users and potential to conserve scarce maintenance resources highlights other key areas that would be aided by the technology. The quality of the UAV-based inspection may be better than human-operated method. It can obtain higher quality images by sending the camera close to the target area. It also reaches the target that is hard to be made by a human. Ultimately, this case study and evaluation of key quantitative indicators, present significant reasoning to support the wider deployment of UAVs as a tool for bridge condition inspections. However, it must be additionally noted, that there are other cost and regulatory factors not highlighted in this case study, which also create resistance.

5.6 The developed UAV system for level-2 bridge inspection

The UAV being developed at the Griffith Robotics Laboratory is controlled manually and (semi) autonomously (see Fig. 6). The UAV system contains two modules: a flight controller and a SLAM module. The flight controller uses a Pixhawk Autopilot Module that contains IMU to aid in keeping the UAV stable during flight. An onboard barometer can be used to stabilise the height of the UAV. With the addition of a GPS unit, the Pixhawk can even fly the UAV autonomously; through GPS waypoints uploaded via a ground station computer. The UAV has two existing communication links; one link to a 2.4 GHz radio transmitter, used by an operator for manual control, and a 915 MHz radio link that transmits telemetry data and commands to and from a ground station computer. A communication protocol called MAVLink is used for communication between the UAV and the ground station computer.

Table 3 Basic cost comparison for disbursements

Inspection Disbursement	Manual Inspections	UAV Based Inspection
Traffic Control	$640	$320
Underbridge Inspection Unit	$2000	-
Bridge Inspectors	$1200	$750
TOTAL	$3840	$1070

(a) Eight-armed UAV (b) Gimbal for Lidar

Fig. 6 UAV system developed at Griffith University

The SLAM module scans the environment using a light detection and ranging (Lidar) sensor and builds a 3D map for localisation. The localisation is an important task to identify the current location of the UAV and the camera, as the GPS signal does not reach the UAV when it is under the bridge. A Raspberry Pi B+ is used for the SLAM operation. It controls two gimbals: one for a camera and another for a Lidar, Hokuyo UTM-30LX. The Raspberry Pi stores images taken by the camera into an SD card and sends it to the ground station computer simultaneously. The computer builds the 3D map, identifies the current location of the UAV without any GPS information and sends the instructions of the next movement to the flight controller. The computer analysis the images using the techniques of feature extraction and pattern recognition (Chanda *et al.* 2014).

6. Challenges for UAV implementation

Whilst the depth of research and investment are driving the advancement of commercial UAV applications, and showing great promise in the process, UAVs are still considered to be in the primitive stages. With the investment spread across a range of sectors, there still remains the common objective for all industries, which is to develop an autonomous system that can be used to reduce the cost of operations. More specifically for bridge asset management, there remain several challenges that prevent the defining goal of integrating UAVs into bridge condition inspections. As presented below are a summary of these hindrances, which are to be addressed in order for aerial-based condition inspections to be implemented.

6.1 Regulation of governing authorities

Regulatory standards and requirements ultimately govern the operational capabilities and the boundaries of the UAV technology. Whilst the development of UAVs has seen the classification of advanced UAVs, based on their ability to utilise autonomous technologies, there remains the broad classification of what defines a UAV. Currently, there is no distinction between different operational types of UAVs in Australia. As highlighted by DeGarmo (2004), Australian regulations currently classify the system based on the weight. While implementing a broad classification system reduces administrative complexity, it fails to recognise the operational differences between different technologies. Consequently, without having a well-defined classification and regulation scheme for different aerial systems, the prospect of introducing a UAV-based inspection system for overall bridge condition assessments remains unfeasible for bridge agencies. Current Civil Aviation Safety Authority (CASA) regulations (2002) dictate that 30 m of clear space must separate the public and vehicles, preventing the operation of the technology over live traffic. Alternatively, the operation of the aircraft over populated area must be at a height less than that for which, if the system fails, it would fall clear of the general public. This stipulation, whilst ensuring safety to the travelling public, prevents the operation of UAVs for the inspection of the bridge deck and approach elements. While UAVs remain a viable option for substructure and superstructure elements where there is no underpass, the economic feasibility of acquiring a UAV inspection system remains questionable.

What is identifiably the most significant obstacle to the practice of aerial-based bridge condition inspections is the training and certification associated with operating the vehicles. The CASR-101 (Civil Aviation Safety Authority, 2002) regulations attempt to distinguish between the classification of a UAV and a model aircraft, where the latter is purely used for leisure or sport. For commercial use, the term “UAV” is used, requiring all operators to obtain licencing and prove competency for all UAVs that are to be used, regardless of the autonomous capabilities (DeGarmo 2004). While UAVs are capable of eliminating bridge inspection units and equipment and reducing the requirements of traffic management, the time consumed and costs accumulated through addressing pilot certification requirements potentially negates these benefits. As part of these certification requirements, it is required that flight training be conducted, where controllers undertake practical training, enabling them to demonstrate their ability to operate the UAV in potential conditions and how to deal with emergencies or malfunctions. While there are no specific training courses that are to be undertaken or training hours to be logged, the controllers are to demonstrate their knowledge and skills through both a written examination and initial flight check (Civil Aviation Safety Authority, 2002). It is difficult to quantify the costs incurred for training, as each organisation and company will differ in their procedures. However, it is estimated by the CASA (2014), that the cost of the operators certificate application and approval alone can amount to $5000.

Although CASR-101 (Civil Aviation Safety Authority, 2002) regulation stipulates the operating conditions and regulations, in some instances, it is required that UAV operations be given formal operating approval. For bridge condition inspections, this approval is required where operations occur in controlled airspaces or with large UAVs. Whilst the operating costs and resource utilisation during inspections are significantly decreased, the associated planning increases significantly. Given that project planning consumes the budget allocated to a project, having to complete the relevant documentation places additional constraints upon the technology and reduces the potential cost-efficiency.

Under the CASA’s regulation (2002), insurance coverage is required for the operation of UAVs to address the associated legal liabilities. As highlighted by Gambold (2011), insurance costs for the UAV operations are often exorbitant, which is limiting their expansion in commercial applications and civil airspace. It is noted by RPAS Training and Solutions (2013), that UAV

Public Liability Insurance can amount to $4000-$6000 per annum. When combining this cost with that of purchasing the equipment, insurance, operations manuals, training and further certification, the cumulative establishment cost alone can easily exceed $15000-$20000. Given this, the feasibility of aerial condition inspections becomes improbable based on economic evaluation. Nevertheless, the price of a UAV and associated components are getting cheaper, the method of control is more safe and intelligent and image analysis techniques are more effective.

While there are significant constraints that largely limit the ability of organisations to conduct inspections using in-house UAVs and operators, there remains opportunities for companies to trial the technology and verify whether it may be integrated into their practices. With the recent drive for more inexpensive and advanced UAVs, the market for the technology has expanded rapidly. In light of this, countless new small-scale companies and subconsultants have arisen, who possess commerical UAV licences and operate their own drones. These subconsultants offer organisations an opportunity to trial the technology for applications ranging from aerial surveillance, aerial imagery and 3D photogrammetric modelling.

6.2 Limitations for superstructure and substructure components

Although the jurisdiction of the CASA (2002) limits the operation of UAVs for condition state inspections to superstructure and substructure components, there remains the additional limitation for bridges that contain road underpasses. Given that safety remains a key priority for the deployment of new technology and the associated government regulations, UAVs are unfeasible for substructure and superstructure components. As demonstrated in Fig. 7, the clearance height between the road and superstructure prevents the use of a UAV as it fails to comply with CASR-101 (Civil Aviation Safety Authority, 2002) regulations and has the potential to significantly affect the safety of the travelling public. This scenario where the location of a supplementary road, or underpass is present, prevents the use of a UAV and limits the number of prospects where aerial-visual condition inspections can be conducted.

Fig. 7 Deck-unit bridge with road underpass (U.S. Department of Transport, 2005)

6.3 Visual observation

Whilst operating a UAV, it is imperative under CASA regulations (2002) and job safety assessments, that the drone remains within a visual line of sight (VLOS) where the operator can clearly note the location in relation to other obstacles. As noted in CASR-101(Civil Aviation Safety Authority, 2002), the purpose of remaining within the VLOS is to ensure that the operator maintains the ability to observe the location of the vehicle in relation to other objects or bridge elements, such that collisions can be avoided.

Bridge structures with multiple spans and waterways present another hindrance for the technology. As the operation of the UAV would be conducted from the approach batters or pathways adjacent to the waterways, in some instances, it is difficult to observe the location of the UAV in relation to superstructure and pier elements. Despite the use of a ground station with real-time visualisation, assessing the proximity to individual components remains a challenge. Ensuring that operators possess the adeptness necessary to navigate these situations presents another encumbrance to the deployment of a UAV-based inspection method. This additional training, certification and instrumentation incur supplementary costs, which significantly reduces the return on investment. Alternatively, to ensure that the UAV remains within the VLOS, boats or other access methods may be used. However, this requires additional time and resources for planning and operation, reducing the cost-effectiveness of UAV inspections.

6.4 Fail-safe programming and obstacle avoidance

As mentioned above, there exists the potential for operations to fall outside the Visual Line of Sight, presenting the opportunity for collisions to occur or a loss of contact with the vehicle. For bridge condition inspections, collisions are likely to occur with static obstacles, such as columns or girders. In these instances where a visual line of sight cannot be maintained, there is the requirement for fail-safe programming and provisions to be made to ensure collisions are passively prevented.

Utilising UAVs for bridge condition inspections presents the potential for system failures, such as the loss of radio contact between the operator and the UAV. In this event a flight termination system (FTS) or autonomous recovery system (ARS) would enable the UAV to return to a predefined location, such as the ground station. Whilst these systems are not obligatory by CASA regulation, importance is placed on their inclusion when operation is close to populous areas (Civil Aviation Safety Authority, 2002). In a study by DeGarmo (2004), it is highlighted that system failures not only present a safety risk, but more importantly, will undermine all previous work completed to attain government and regulatory support. Hence, preventing incidents and including additional fallback mechanisms and redundancies remains a key area of concern. Although autonomous operations utilising pre-programmed routes can reduce the reliance upon the operator's capability and the likelihood of collisions, there still remains the necessity to introduce preventative-programming.

Typical ground-based robots negate the need for sense-and-avoid technologies that passively prevent collisions with other vehicles or obstructions. With aerial-based vehicles, there is the need for greater awareness from the operator and in-built sensory technology that has the capacity to detect potential conflicts and take appropriate action. A vast majority of obstacle avoidance systems used in UAVs involve passive technology which include optical flow sensors or laser ranging. With laser ranging and other sensory equipment, they often add weight to the payload, requiring vehicles that are more capable of sustaining the additional load. This ultimately presents another challenge to the deployment of UAVs as including avoidance systems or developing visual-based detection algorithms consumes resources and imposes further establishment costs, mitigating financial benefits of aerial technology.

6.5 SLAM for localising UAVs

GPS is generally used by UAVs for navigation. However a GPS signal is not always available. Areas where GPS may be denied include inside structures, underneath large bridges and where tall buildings may shadow the signal.

An alternative for localizing UAVs is the use of SLAM which is a statistical estimation technique where a UAV can build a map of an unknown area, while simultaneously deducing its location within this map (Durrant-Whyte and Bailey, 2006). SLAM has been solved in theory, with success derived through the CSIRO Zebedee handheld 3D mapping system (Walker 2014). To implement the SLAM process for UAV-based bridge inspections, a UAV measures and observes the environment around it using sensors. The positions of landmark features in the environment are identified, and a map containing the landmarks is created (Gupta and Ashraf 2012). As the UAV moves, it observes the landmarks and matches the position of the landmarks to the known landmarks in the map.

7. Overcoming current constraints

Although the immediate prospect of implementing an aerial-based bridge inspection system is questionable at best due to commercial limitations, this has remained a significant area of interest for bridge asset management. With the technological advancements and drive for a flexible, low-cost aerial platform, there exists the potential for future developments combined with changes to government regulations, to overcome current limitations. With civil aviation authorities and numerous local and government organisations working hand-in-hand to mitigate regulatory limitations and accommodate for UAVs in civil airspace, there is a compelling case for the eventual integration into bridge condition assessments. However, it is only through open dialogue and targeted discussions about the borders to the UAV-based inspections with relevant stakeholder groups, that the potential of aerial-based inspections will be fully realised.

8. Conclusions

While UAVs present significant potential for bridge asset management, the operating complexities and regulatory requirements hinder the wider deployment. Current CASA regulations restrict and limit the operation of UAVs when in close proximity to infrastructure and the travelling public, which ultimately prevents the use of aerial inspection systems for deck and approach components. Whilst substructure and superstructure components may be inspected by multicopter technology, much of the financial advantages for reducing resource utilisation are alleviated by the operational requirements for technology that falls under the jurisdiction of CASA.

Though the development of inexpensive and flexible platforms has reduced the operational complexity and increased the broader use for commercial applications, the use of UAVs is still constrained by the requirements for training and certification. These licencing requirements and administrative legalities will continue to negate any financial and socioeconomic benefits.

Although the immediate prospect of realising an aerial-based approach to bridge condition inspections is challenging at best, this is to remain a significant area of interest for the near future. With the technological advancements and drive for more flexible, low-cost aerial platforms, there exists the potential for future developments combined with changes to government regulations, to overcome current limitations. With civil aviation authorities and numerous organisations working hand-in-hand to mitigate regulatory limitations and accommodate for UAVs in civil airspace, there is a compelling case for their eventual integration into bridge condition assessments.

References

Adams, S.M., Levitan, M.L. and Friedland, C.J. (2013), *High Resolution Imagery Collection Utilizing Unmanned Aerial Vehicles (UAVs) for Post-Disaster Studies*, *ASCE*, Miami, Florida, USA.

Advanced Highway Maintenance and Construction Program (2008), *CALTRANS Bridge Inspection Aerial Robot*, California Department of Transportation, California.

Aibotix GmbH (2014), *Bridge Inspection*. [Online] Available at: http://www.aibotix.com/-bridge-inspection.html [Accessed 24 March 2014].

Choset, H. (2000), *Bridge Inspection with Serpentine Robots*, Highway IDEA Project 56, Washington D.C., USA.

Chanda, S., Bu, G., Guan, H., Jo, J., Pal, U., Loo, Y.C. and Blumenstein, M. (2014), "Automatic bridge crack detection – a texture analysis-based approach", *Artificial Neural Networks in Pattern Recognition*, 193-203.

Civil Aviation Safety Authority (2002), *AC 101:1(0) Unmanned Aircraft and Rockets*, Civil Aviation Safety Authority, Australia.

Civil Aviation Safety Authority (2014), *Applying for an Operator's Certificate (OC)*. [Online] Available at: http://www.casa.gov.au/scripts/nc.dll?WCMS:STANDARD:: pc=PC_100377 [Accessed 1 April 2014].

DeGarmo, M.T. (2004), *Issues Concerning Integration of Unmanned Aerial Vehicles in Civil Airspace*, Mitre Corporation, November.

Department of Transport and Main Roads (2002), *Part 5: Bridge Asset Maintenance*, Queensland Government, Queensland, Australia.

Department of Transport and Main Roads (2014), *Part 3: Work on Roads*, Queensland Government, Queensland, Australia.

Durrant-Whyte, H. and Bailey, T. (2006), "Simultaneous localisation and mapping (SLAM): Part I the essential algorithms", *IEEE Robot. Autom.Mag.*, **13**(2), 99-110.

Gambold, K.A. (2011), *Unmanned Aircraft System Access to National Airspace*, Technical and Air Safety Committee, USA.

Gupta, S. and Ashraf, J. (2012), "Vision based simultaneous localization and mapping", *Int. J. Comput.Eng. Management*, **15**(3), 50-53.

Hachem, Y., Zografos, K. and Soltani, M., (1991), "Bridge Inspection Strategies", *J. Performance of Constructed Facilities*, **5**(1), 37-56.

Heintz, F., Piotr, R. and Doherty, P. (2007), "From images to traffic behavior - a UAV tracking and monitoring application", *Proceedings of the 10th International Conference on Information Fusion*, Quebec, Canada, July.

Hubner, D. and Barton, D. (2003), *Guide to Road Design Part 3: Geometric Design*, Austroads, Sydney, Australia.

Irizarry, J., Gheisari, M. and Walker, B.N. (2012), “Usability assessment of drone technology as safety inspection tools”, *J. Infor. Tech. Constr.*, **17**(1), 194-212.

Kamya, B. (2010), “*Bridge inspection: Are we getting it right?*”, Bridge Maintenance, Safety, Management and Life-Cycle Optimisation, Taylor & Francis Group, London.

Koonce, J., Demski, T., Rowe, M. and Morriss, N. (2011), “Bridge inspection access to minimize operational impacts”, *Proceedings of the AREMA 2011 Annual Conference*. Minneapolis, USA, September.

Lattanzi, D.A. and Miller, G. (2013), “A prototype imaging and visualisation system for robotic infrastructure inspection”, *Proceedings of the Structures Congress 2013*, *ASCE*, Pittsburgh, Pennsylvania, USA, May.

Neitzel, F. and Klonowski, J. (2011), “Mobile 3D mapping with a low-cost UAV system”, *Int. Archives Photogrammetry, Remote Sensing and Spatial Information Sciences*, **38**(1), 1-6.

Oh, J., Jang, G., Oh, S., Lee, J.H., Yi, B., Moon, Y.S., Lee, J.S. and Choi, Y. (2009), “Bridge inspection robot system with machine vision”, *Automat. Constr.*, **18**(1), 929-941.

PTV Planung Transport Verkehr AG (2013), *PTV VISSIM 6.0*, Karlsruhe, Germany.

Puri, A. (2005), *A Survey of Unmanned Aerial Vehicles (UAV) for Traffic Surveillance*, South Florida, USA.

RIEGL Laser Measurement Systems GmbH (2014), *RIEGL Laser Measurement Systems*. [Online] Available at: http://www.riegl.com/media-events/newsletter/1012-vz-400-marine-mapping-demonstration/ [Accessed 27 March 2014].

RPAS Training and Solutions (2014), *UAV/Drone/RPA Training for CASA RPC or UAV Controller Certificates*. [Online] Available at: http://www.rpastraining.com.au/ [Accessed 27 March 2014].

Siebert, S. and Teizer, J. (2014), “Mobile 3D mapping for surveying earthworks projects using an unmanned aerial vehicle”, *Automat. Constr.*, **41**(1), 1-14.

Srinivasan, S., Latchman, H., Shea, J., Wong, T. and McNair, J. (2004), “Airborne traffic surveillance systems: video surveillance of highway traffic”, *Proceedings of the ACM 2nd International Workshop on Video Surveillance & Sensor Networks*, New York, USA, October.

The National Work Zone Safety Information Clearinghouse (2013), *Fatalities in Motor Vehicle Traffic Crashes by State and Work Zone (2012).* [Online] Available at: http://www.workzonesafety.org/crash_data/workzone_fatalities/2012 [Accessed 24 March 2014].

Transport Research Board (2000), *Highway Capacity Manual*, National Academy of Sciences, Washington, USA.

U.S. Department of Transport (2005), *Farm Lane Underpass*. [Online] Available at: http://contextsensitivesolutions.org/content/case_studies/farm_lane_underpasses/# [Accessed 30 March 2014].

Walker, S. (2014), “The Surveyor’s 21st Century Tools”, *Eng. Mining J.*, **215**(7), 28.

Wang, J., Lin, Z. and Li, C. (2004), “Reconstruction of buildings from a single UAV image”, *Proceedings of the International Society for Photogrammetry and Remote Sensing Congress*, Beijing, China, July.