AN ABSTRACT OF THE THESIS OF

Matthew N. Gillins for the degree of Master of Science in Civil Engineering presented on November 21, 2016.

Title: Unmanned Aircraft Systems for Bridge Inspection: Testing and Developing End-to-End Operational Workflow.

Abstract approved:

____

Christopher E. Parrish

Bridge inspections are vital for monitoring the health and serviceability of transportation infrastructure throughout the world. However, inspections can be logistically-challenging, expensive, and dangerous. For example, inspections may require climbing, as well as the use of scaffolding, ladders, rescue boats, bucket trucks, and/or under-bridge inspection vehicles. Small, multirotor unmanned aircraft systems (UAS) offer a potential means of overcoming or alleviating some of these challenges. Among the primary benefits of UAS for inspections are the ability to maneuver adeptly in 3D space, change view angles, and acquire high-resolution imagery, enabling the inspector to view (in real time and/or post-flight using post-processing enhancements, as needed) bridge elements in difficult-to-access locations, all while keeping both feet firmly on the ground. As transportation departments, inspection firms, and service providers increasingly recognize these potential benefits, interest in UAS for bridge inspections is growing rapidly. While a number of UAS bridge inspection projects have been documented in published reports and case studies, the rate of change of both UAS

technology and associated regulations necessitates additional research and development, especially with regards to operational aspects of UAS bridge inspection. The purpose of this study was to develop, test and document an end-to-end operational workflow for UAS bridge inspections, with a particular focus on regulatory and safety aspects. Since it is recognized that UAS are simply one tool for this particular application, another key focus on this study was on investigating which aspects of bridge inspection can and cannot be aided by UAS. As part of the study, three bridges in Oregon, representing different bridge types, conditions and locations, were inspected using small, multirotor UAS.

Unmanned Aircraft Systems for Bridge Inspection: Testing and Developing End-to-End Operational Workflow

by
Matthew N. Gillins

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented November 21, 2016
Commencement June 2017

Master of Science thesis of Matthew N. Gillins presented on November 21, 2016

APPROVED:

Major Professor, representing Civil Engineering

Head of the School of Civil and Construction Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Matthew N. Gillins, Author

ACKNOWLEDGEMENTS

The author expresses sincere appreciation to his committee members Michael Olsen, Jihye Park, and Geoff Hollinger for the time and assistance in reviewing this thesis. The author would also like to acknowledge Oregon Department of Transportation for their sage advice as well as for funding this project. Without their help the study would not have been possible or successful. Also the assistance from VDOS and Complier Enterprise in planning and gaining authorization for operations was vital to the project. Lastly, a special thanks to students from Oregon State University, Farid Javadnedjad, Chase Simpson, and Jonathan Burnett for their assistance in gathering the data presented in the paper.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

1.0 Introduction

Humans have constructed bridges since prehistory, due to the continual need to transport people and goods safely and efficiently in locations with limited alternative paths. However, bridges can be dangerous to cross if not properly built or maintained. One of the responsibilities of civil engineers today is to inspect bridges for defects that may compromise the structural integrity of the bridge. A number of challenges exist in bridge inspection, due to the difficult terrain where bridges are constructed, traffic, the stringent requirements that must be met, and other factors. Today researchers are exploring new technologies that can potentially improve safety in bridge inspection by decreasing the reliance on climbing, bucket trucks, boats and other potentially-hazardous activities. Unmanned Aircraft Systems (UAS) are a potential tool help augment bridge inspections. Collecting imagery through UAS technology could allow for a remote inspection in which the inspector can view the elements of the bridge in a safe location.

1.1 Thesis Format

This document follows the manuscript thesis format.

Chapter 2 presents the manuscript that is in preparation for submission to the ASCE Journal of Bridge Engineering on an End-to-End operational workflow for performing UAS based bridge inspections, as well as three test bridges to which this workflow was applied to evaluate the effectiveness of the technology for this application.

Chapter 3 is an appendix that presents the results of a communication tower inspection that was done with a UAS with a slightly modified methodology than the bridge inspections. This imagery and results are included to show the potential for additional structural inspections that can benefit from UAS technology.

2.0 Manuscript

Title: **Unmanned Aircraft Systems for Bridge Inspection: Testing and Developing End-to-End Operational Workflow**

Target Journal: *Journal of Bridge Engineering*

Authors: Matthew N. Gillins

2.1 Abstract

Bridge inspections are vital for monitoring the health and serviceability of transportation infrastructure throughout the world. However, inspections can be logistically-challenging, expensive, and dangerous. For example, inspections may require climbing, as well as the use of scaffolding, ladders, rescue boats, bucket trucks, and/or under-bridge inspection vehicles. Small, multirotor unmanned aircraft systems (UAS) offer a potential means of overcoming or alleviating some of these challenges. Among the primary benefits of UAS for inspections are the ability to maneuver adeptly in 3D space, change view angles, and acquire high-resolution imagery, enabling the inspector to view (in real time and/or post-flight using post-processing enhancements, as needed) bridge elements in difficult-to-access locations, all while keeping both feet firmly on the ground. As transportation departments, inspection firms, and service providers increasingly recognize these potential benefits, interest in UAS for bridge inspections is growing rapidly. While a number of UAS bridge inspection projects have been documented in published reports and case studies, the rate of change of both UAS technology and associated regulations necessitates additional research and development, especially with regards to operational aspects of UAS bridge inspection. The purpose of this study was to develop, test and document an end-to-end operational workflow for UAS bridge inspections, with a particular focus on regulatory and safety aspects.

Since it is recognized that UAS are simply one tool for this application, another key focus on this study was on investigating which aspects of bridge inspection can and cannot be aided by UAS. As part of the study, three bridges in Oregon, representing different bridge types, conditions and locations, were inspected using small, multirotor UAS.

2.2 Introduction

Large structures present significant challenges to workers around the world. Bridges, which are vital to transportation infrastructure, serve as the most common method of transporting people and goods across difficult and sometimes dangerous terrain. According to the recent ASCE report card (ASCE 2013), over ten percent of the nation's bridges are rated as structurally deficient, with an average age of 42 years. The risks associated with deficient bridges spurred the Federal Highway Administration (FHWA) to mandate that states visually inspect and inventory federal-aid highway system bridges at least once every two years (23 CFR Part 650). These mandatory biennial bridge inspections are important for assessing the safety of a bridge. However, the inspections can be dangerous, as inspectors are often required to stand in platform trucks, bucket trucks, or under-bridge inspection vehicles in order to access and view necessary bridge elements. Mobilizing such vehicles to bridges can be quite costly. Also, some inspections require extensive climbing, use of temporary scaffolding and ladders, or rescue boats. In addition to the danger to the inspector and vehicle operator, road users also face danger as traffic lanes on the bridge are often closed or reduced during an inspection.

UAS technology is advancing rapidly, and the data collected from UAS are proving valuable across a wide range of application areas, including agriculture, forestry, archaeology, traffic monitoring, and post-disaster response, to name just a few (e.g., Remondino et al., 2011;

Adams et al., 2014; Wood et al. 2017). Eschmann et al. (2013) demonstrated that buildings and other structures could be captured at high resolution, and that the defects were readily visible. Ellenberg et al. (2014) determined that cameras mounted on a UAS could detect cracks small enough to be of interest in visual inspection but did not make a direct comparison to the spatial resolution of the human inspector at arm's length. Hallermann and Morgentahal (2013) have concluded that UAS can be an effective tool for inspecting several different types of structures in difficult and dangerous environments. These researchers were able to capture high resolution imagery of industrial chimneys and also historical buildings. Sa et al. (2015) inspected a high-reaching pole with a UAS. Their findings showed that locations that are difficult to physically occupy can be viewed remotely using UAS.

The low operation costs of UAS allow for frequent flights to be performed in the same area enabling time series-based structural health monitoring (SHM). Hallermann et al. (2014) used UAS to monitor large structures such as dams and retaining walls. Displacements in these structures were monitored with the imagery collected from the UAS.

Given the potential benefits, it is no surprise that some investigation has already started in implementing UAS technologies for monitoring bridges. Vaghefi et al. (2012) concluded that many aspects of a bridge inspection could be aided by remote sensing technologies with a UAS. Khan et al. (2015) collected RGB and thermal imagery of a mock up bridge to demonstrate the types of data that can be collected with a UAS. With a thermal camera, they were able to detect possible delamination in the concrete deck of the bridge. Otero et al. (2015) have done several tests in order to demonstrate how UAS can be deployed to aid in a bridge inspection. They were able to capture highly detailed images while flying in high pressure zones created in a gymnasium with large fans, maintain flying proximity of 0.6 – 1.0 meters from the target structure, and detect cracks as small as 0.5 mm in width. Brooks et al. (2015) have been investigating several applications of UAS technology. These researchers have used UAS for traffic monitoring, as well as for three-dimensional reconstruction of sites from aerial imaging. They have also used the technology for bridge inspection work. Specifically, they used the UAS to capture imagery, both RGB and thermal imagery of the bridge deck and apply algorithms to detect deformities on the drive surface. Otero et al. (2015) also identified UAS as a tool to aid bridge inspectors. They were able to perform many tests indoors to evaluate the technology in hazardous flying situations, followed by limited inspections on bridges as well as on high mast luminaires (HMLs). A goal of the work was to investigate whether the images acquired are comparable to the images that would be acquired with a camera during a conventional inspection. They concluded that there are benefits of using UAS for structural inspection, but that there are still gaps that need to be addressed by additional research.

Notwithstanding the many contributions of the literature published to date, it is evident that a number of gaps exist in the current state of knowledge associated with UAS structural inspections. Notably, while research conducted to date has nicely illustrated the potential benefits of UAS for structural inspection, most studies conducted to this point have been demonstrations or proof-of-concept studies that have not addressed the operational aspects of implementing UAS technology in a structural inspection program. Questions that have not yet been adequately addressed include:

- What end-to-end operational procedures and workflows should be followed by inspectors, UAS operators, spotters and support personnel to ensure safe and efficient operations?
- What is the return on investment (ROI) from operational use of UAS in bridge inspections, as documented through cost-benefit analysis?

- How do new and proposed Federal and State regulations related to UAS impact operational use?

This paper addresses the first of those unanswered questions, while ongoing work by the research team will address the latter two questions. The considerations that need to be addressed in an end-to-end UAS-based structural inspection are presented as well as results of test inspections of three bridges in Oregon. Although the focus of this paper is on bridges, the results of a test inspection of one communication tower is also shown in the appendix since many of the operational aspects for inspecting a tower with a UAS are similar to inspecting a bridge.

2.3 Background on Bridge Inspection

There are many different types of bridge inspections that can be performed to evaluate and monitor a bridge. AASHTO defines eight different bridge inspections: initial, routine, damage, in-depth, fracture-critical, underwater, routine wading, and special inspections. (AASHTO 2011). The most common of the inspections is the routine inspection, which is primarily a visual inspections used to search for and identify any defects on the bridge. If defects or damage are found, in-depth or damage inspections are then prescribed. These inspections have a more “hand’s on” requirement in which probing, scraping, and contacting the bridge in necessary. It is important to note that each type of inspection has both visual and physical inspection requirements.

The FHWA requires that every bridge inspection is accompanied with a bridge inspection report. The reports contain information on what are classified as inventory items, condition ratings, and appraisal items (Ryan 2008). The ratings are used to determine the serviceability and maintenance that is needed for the bridge.

Inventory and Condition ratings both items pertain to a bridge's characteristics. Inventory ratings are items are that permanent characteristics, which only change when the bridge is altered in some way, such as reconstruction or load restriction. Condition ratings are used to describe the existing, in-place bridge as compared to the as-built condition. Condition ratings are typically coded by the inspector and include things such as the bridge deck, superstructure, and substructure.

Appraisal items are used to evaluate a bridge in relation to the level of service which it provides on the highway system of which it is a part. The structure will be compared to a new one which is built to current standards for that particular type of road. Appraisal rating items include clearances, geometry, and alignments.

2.4 Methods on UAS for Bridge Inspection

An end-to-end workflow for UAS structural inspections should include, at a minimum, the following components: (1) selection of UAS, (2) flight planning, (3) development of a safety plan, (4) data acquisition, and (5) data processing. The following sections describe the workflow used in this study. Figure 1 shows the workflow presented in this paper.

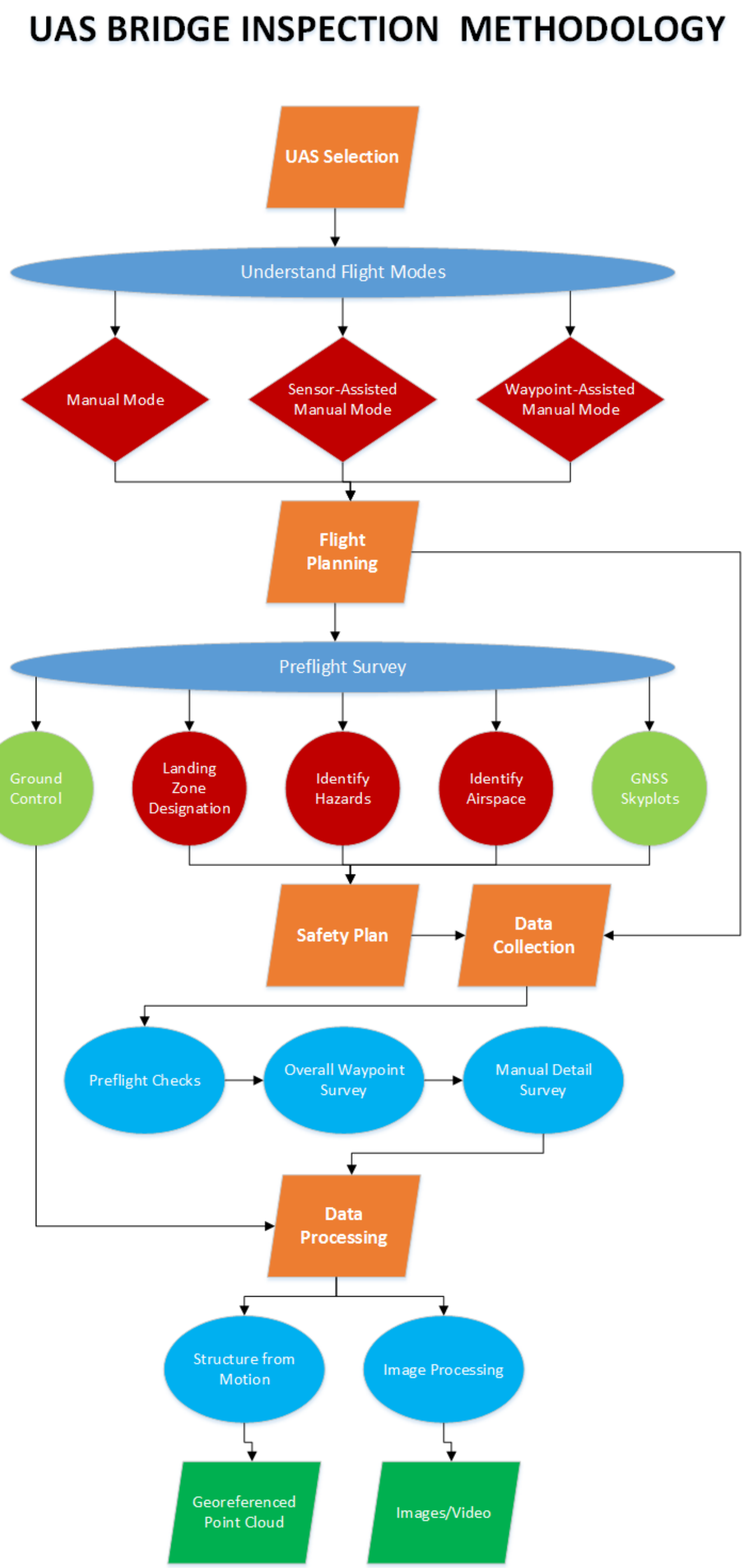

Figure 1. UAS based bridge inspections workflow

2.4.1 UAS Selection

A number of components and subsystems comprise an Unmanned Aircraft System (UAS). The U.S. Federal Aviation Administration (FAA) defines a UAS to not only include the unmanned aircraft, but also “all of the associated support equipment, control station, data links, telemetry, communications and navigation equipment, etc., necessary to operate the unmanned aircraft.” The FAA further defines an unmanned aircraft as “the flying portion of the UAS, flown by a pilot via a ground control system, or autonomously through use of an on-board computer” (FAA, 2015).

An unmanned aircraft is defined as any vehicle that flies without a human onboard. Considering this broad definition, a wide range of unmanned aircraft are in operation today. They vary in size, weight, payload, and endurance, as well as in the types of applications they can support. Examples of unmanned aircraft are fixed-wing gliders, (quad-, hexa-, octo-) copters (collectively known as multicopters), helicopters, airships, balloon systems, and more broadly, any unmanned vehicle with the ability to fly auto-controlled by using processors on-board, by remote controls with human supervision, or by another aerial vehicle under coordination (Pajares, 2015).

While the range of types and sizes of UAS are broad, the most common types in civilian operations fall in the category of small UAS (sUAS). The FAA defines a sUAS as any unmanned aircraft that weighs less than 55 lbs. Table 1 divides the sUAS into three common subclasses: fixed-wing gliders, multicopters, and helicopters. This table summarizes the advantages of each subclass from a study done by Otero et al. (2015), and it also gives examples of professional-grade systems on the market. Of course, there also exist a large number of consumer-grade options for each of these subclasses.

Table 1. Subclasses of sUAS and some examples (after Otero et al. 2015)

Subclass	Advantages	Examples
Fixed-wing gliders	-Capable of flying at greater speeds -Able to carry larger payloads than multicopters -Able to glide in flight which reduces battery or fuel consumption (longer endurance and capable of flying greater distances)	Trimble UX-5; senseFly eBee; Topcon Sirius Pro; Honeycomb AgDrone
Multicopters (e.g., quadcopters, hexacopters, octocopters)	-Highly maneuverable (can make sharp turns in flight) -Able to hover in place -Capable of vertical take-offs and landings and do not require runways or catapults	Leica Geosysems Aibot X6; senseFly albris; Riegl RiCOPTER; Trimble ZX5
Helicopters	-Capable of near vertical take-offs and landings -Capable of carrying larger payloads than multicopters -Longer flight endurance than multicopters—particularly if using gasoline powered engines	Alpha Unmanned Systems Sniper; Swiss UAV KOAX X-240 MK II

Considering the strengths and weaknesses of each of the subclasses of UAS, the multicopter is highly preferred for inspection work because of its superior maneuverability, ability to perform vertical take-offs and landings (i.e., reduction in the required size of the landing zone), and ability to hover in place. The main drawback of multicopters are that they typically have shorter flight times compared to the other two subclasses.

2.4.2 Flight Planning

Flight planning is critical for the safety and success of a UAS-based inspection. There are many laws and regulations in place to help ensure the safety of airborne operations (e.g., FAA, 2016). The planner should ensure that all operations are in compliance with the laws and regulations. In addition, the planner needs to be aware of the different flight modes available for the UAS and should have a thorough understanding of how it will execute failsafe routines during unexpected problems, such as loss of data link between the aircraft and the ground control station, malfunction of the onboard flight-assistance sensors, or degradation of wireless signals. Once familiar with the UAS and mindful of its flying capabilities and failsafe routines, it is best practice for the planner to next visit the site, identify safe and open location(s) for take-offs and landings, determine safe flight paths, and note any obstacles along possible flight paths.

Depending on the UAS, numerous flight modes are available for planning a safe and efficient mission. Although a number of modes are available, the common flight modes on most sUAS can be categorized into: (1) manual flights, (2) sensor-assisted manual flights, and (3) waypoint-assisted flights. Table 2 summarizes advantages of the latter two categories.

During manual flights, the pilot uses a remote controller (e.g., radio controller, laptop, tablet or other mobile device) for sending thrust, roll, pitch, and yaw signals to the aircraft and does not rely on assistance from other sensors. Because of the lack of sensor assistance, this mode is less safe and is not recommended for performing structural inspections. However, the operator should be trained in executing manual flights if there is an emergency or malfunction of an assisting sensor onboard the aircraft.

Sensor-assisted flight is the most common type amongst UAS operators. This mode also requires the pilot to use a remote controller to send thrust, roll, pitch, and yaw signals to the aircraft, but it also takes advantage of onboard flight-assistance sensors. Depending on the UAS, GNSS, ultrasonic, barometric, and inertial sensors may be used. GNSS, inertial and barometric sensors are especially prevalent, and they enable a rotary aircraft to hover in place when the operator stops applying thrust. Without GNSS, the aircraft may drift or wander horizontally rather than hover in place, especially in the presence of wind or other lateral forces. Inspections often require flights very close or possibly even underneath a feature of interest (e.g., beneath a bridge) in order to capture imagery with sufficient resolution. Flying close to or underneath structures may result in GNSS signals being blocked or degraded due to multipathing. Thus, sensors other than GNSS may be required for horizontal positioning during a structural inspection. For example, ultrasonic sensors may be used to hold the aircraft a fixed distance from a large object. For some aircraft, ultrasonic sensors can also be used to warn the operator of an obstacle near the aircraft.

During sensor-assisted flight, many operators will also commonly use first-person view (FPV) technology which broadcasts live video from a camera onboard the unmanned aircraft to a monitor in front of the operator. FPV helps the operator navigate the aircraft around obstacles, as the video provides enhance perspective of the position of the aircraft. Using FPV and while hovering or slowly flying, the camera can be pointed and shuttered in order to collect specific imagery of a feature on the structure. The camera is often shuttered by selecting a switch on the remote controller, or by using an intervalometer with specified intervals.

Waypoint-assisted flights are useful for systematically capturing images and video of the structure. Using mission planning software, the planner can insert waypoints where the camera will be oriented and shuttered, create flight paths and trajectories, and adjust the flying speed as illustrated in Figure 2. Once satisfied, the mission plan is uploaded to the aircraft. During flight, the aircraft uses GNSS and inertial sensor(s) for positioning and executing the mission. If necessary, the operator can pause or abort the mission.

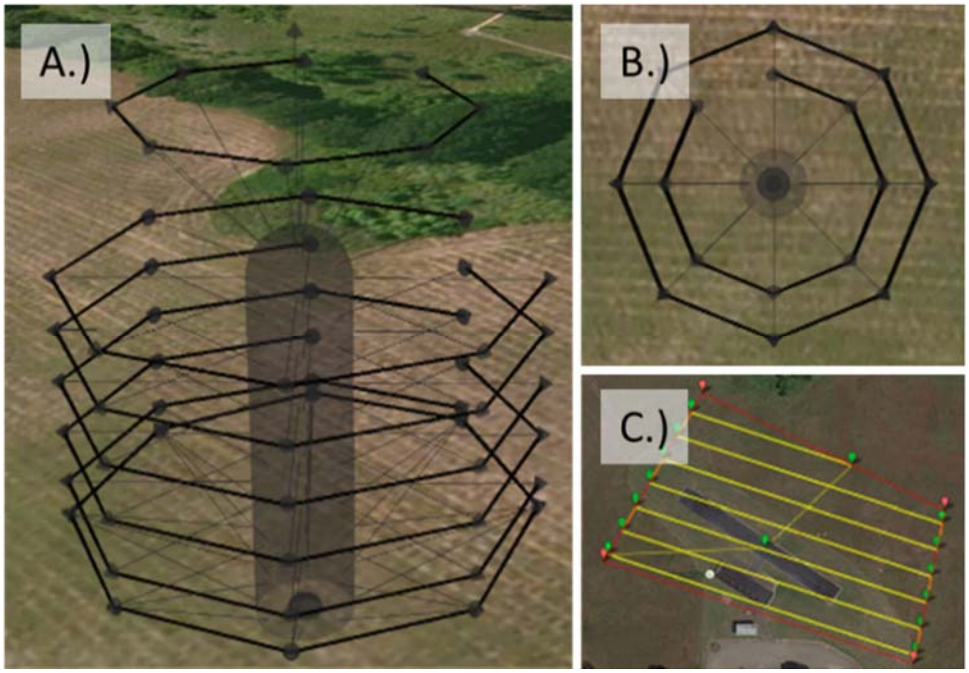

Figure 2. Waypoint-assisted flight missions; A.) 3D view of a cylinder flight plan; B.) Plan view of cylinder flight plan; C.) Plan view of a horizontal mapping flight plan

Waypoint-assisted flight is particularly useful for systematically collecting overlapping and comprehensive imagery of a feature of interest. This flight method is advantageous for inspections because it provides multiple images of the same part of the structure from different pointing angles, and it is excellent for generating synoptic views. The method also greatly reduces the human interaction with the ground station during flight as compared with the other flight modes described above. Another benefit is that by using photogrammetry principles and a computer vision technique known as structure from motion (SfM), it is possible to orthorectify and mosaic the overlapping imagery and create a 3-D point cloud of the structure (Eltner et al. 2016; Furukawa and Ponce 2010; Snavely et al. 2006; Javadnejad and Gillins 2016). The weakness of the waypoint-assisted flight method is that most UAS rely on GNSS for positioning the aircraft and flying to each waypoint in the mission.

Table 2. Comparison of the advantages of flight methods for acquiring data

Sensor-Assisted Flight	**Waypoint-Assisted Flight**
Advantages	Advantages
-Operator can carefully position the camera to view a specific feature of interest	-Overlapping photos can be developed into a 3D model
-Close-up photos	-Systematic flights ensure features are photographed from multiple viewing angles
-Less time	-Less human interaction required

2.4.3 Safety Plan

The creation of safety plans is standard practice for most inspection agencies. Identification of the risks involved with the structure being inspected and the mitigation techniques are logged before the inspection takes place. The purpose of the preflight survey is to identify any special considerations for the site that is to be inspected. A UAS, as a flying platform, must consider obstacles such as trees as well as potential frequency interference of the communications of the ground station to the aircraft. A preflight survey allows the team to observe any potential safety issues from which a safety plan can be created. During this survey the team identifies the following: 1) the best location for a landing zone (LZ) for the aircraft, as well as for the ground station equipment; 2) radio frequencies being broadcast at the inspection site; 3) the height and proximity of any obstacles around the structure of interest; 4) the presence and location of any people, equipment or structures not associated with the inspection; and 5) any other potential dangers, logistical challenges or considerations associated with the site. It is also ideal to set and survey ground control targets on and around the structure to facilitate post processing of the data to be collected by the UAS.

During the creation of the safety plan, the airspace of the site also needs to be identified for determining whether or not any additional permissions will need to be obtained from nearby airstrips/airports. This is done by using the FAA sectional charts which indicates airport locations as well as airspace restrictions. Airspace G is available for flights under most FAA authorizations, but if the site lies within five nautical miles of a towered airport, a letter of agreement with the airport manager is required.

Every hazard noted in the preflight survey needs to have a mitigation technique created for it. Hazards such as drop hazards, trip hazards, and environmental hazards are standard. However, something that is fairly unique to a GNSS dependent flying object is satellite availability. These systems are created with fail safes installed that auto trigger corrective actions when the GNSS signal degrades below a threshold set in the system. The majority of these corrective actions are either a signal to return to the last position for which there was a “good” GNSS solution or to change the flight mode to manual flight. These actions can be problematic when flying near or below a structure, as the degradation of signal is varying depending on the satellite constellation’s geometry. Hence, detailed evaluation of what happens in each corrective action (and possible changes to the default behavior) are necessary for safe UAS-based inspection.

The creation of GNSS satellite availability plots is a common practice in control surveying to determine the best time to collect GNSS data, as they illustrate what periods of time have the highest number of satellites available for a given location. To make one of these plots, the physical obstructions are plotted on a circular plot with azimuth plotted on the angular axis and vertical angles plotted on the radial axis. Utilizing the GNSS almanac, the azimuths and elevations of GPS satellites (as well as GLONASS satellites, if used by the receiver) are plotted over time. If the satellite is in an area that is obstructed, it is assumed that the signal is not reaching the receiver. Using these plots, one could choose the time of day that would result in the highest available GNSS signal strength. Such plots can be used in the planning stage of UAS bridge inspection to assess potential GNSS signal blockage, due to the structure being inspected and other nearby obstructions. This analysis can, in turn, be used to determine the appropriate flight mode and which corrective actions should be implemented if GNSS is lost.

2.4.4 Data Acquisition

After the preflight survey and safety plans are in place, flights are planned and completed with the selected mission parameters and settings to ensure that all desired data is captured in a safe and effective manner. Considerations that are taken into account for the flights are the size of the site, obstacles observed during the preflight survey, and battery capacity of the aircraft. There are a few combinations of procedures that can be followed to ensure a complete inspection. A proposed method of data acquisition is as follows: a first flight, an overall site survey, followed by a manual detail survey.

Once on the site and standard preflight checks have been completed, a first flight test should to be performed. The purpose of this first flight is to verify that the controls and gages of the UAS are functioning correctly. This is generally a short (< 5 min) flight, in which all of the controls (roll, pitch, yaw, and thrust) are tested. The operator should also check that gages and displays are functioning on the ground control station. If the controls are working and gages are displaying acceptable values, the planned flights are ready to be performed.

The overall site survey is important for orientation of the structure as well as to serve as a "backbone" for more detailed imagery collected in the manual detail survey. Making use of waypoints, overhead mapping combined with either point-of-interest or cylinder mapping tools facilitate generation of orthoimagery and 3D point clouds of the site. While the overhead (planimetric or nadir-viewing imagery) is, in many cases, not detailed enough or in the right perspective for visual inspections, the orthoimagery and 3D model can provide important information, such as scale and orientation of the structure.

The manual detail survey is performed if more detailed imagery is needed for a particular site. The imagery from the overall waypoint survey is often not in high enough resolution to see enough detail of the structure. Items such as hardware being properly fastened are often only achievable with close proximity flying that can only be done with a manual GPS-aided flight. Imagery collected while flying in this manner is comparable to what an inspector would see at arm's reach. However, in addition to the UAS's capabilities, the pilot's comfort level, as well as environmental factors, such as variable wind gusts that are common around many bridges, are all factors in determining how close the aircraft can be operated to the structure.

2.4.5 Data Processing

Post-processing of the imagery can provide a wealth of information not available in real-time during the flight. If enough care is taken during the collection of imagery Structure from Motion (SfM) algorithms can be applied to create a three dimensional, georeferenced point cloud of the structure and site (See Figures 3 and 4). The software package Agisoft Photoscan was utilized to do the SfM processing for the images collected at the Crooked River Bridge. This software is capable of aligning and scaling the images, creating dense 3D point clouds, as well as creating meshes and orthophotos of the survey site. (Agisoft 2016)

Figure 3: Georeferenced point cloud of Crooked River Bridge.

The 3D models generated through this additional processing can be used to enable precise geometric measurements. Parameters of interest in this type of analysis may include geometry, crack dimensions, orientation, and even vegetation encroachment. The tools in several software packages can allow the inspector to make these measurements in a safe location instead of being directly on the bridge. Figure 12 shows the detail of the point clouds developed on one of the test sites.

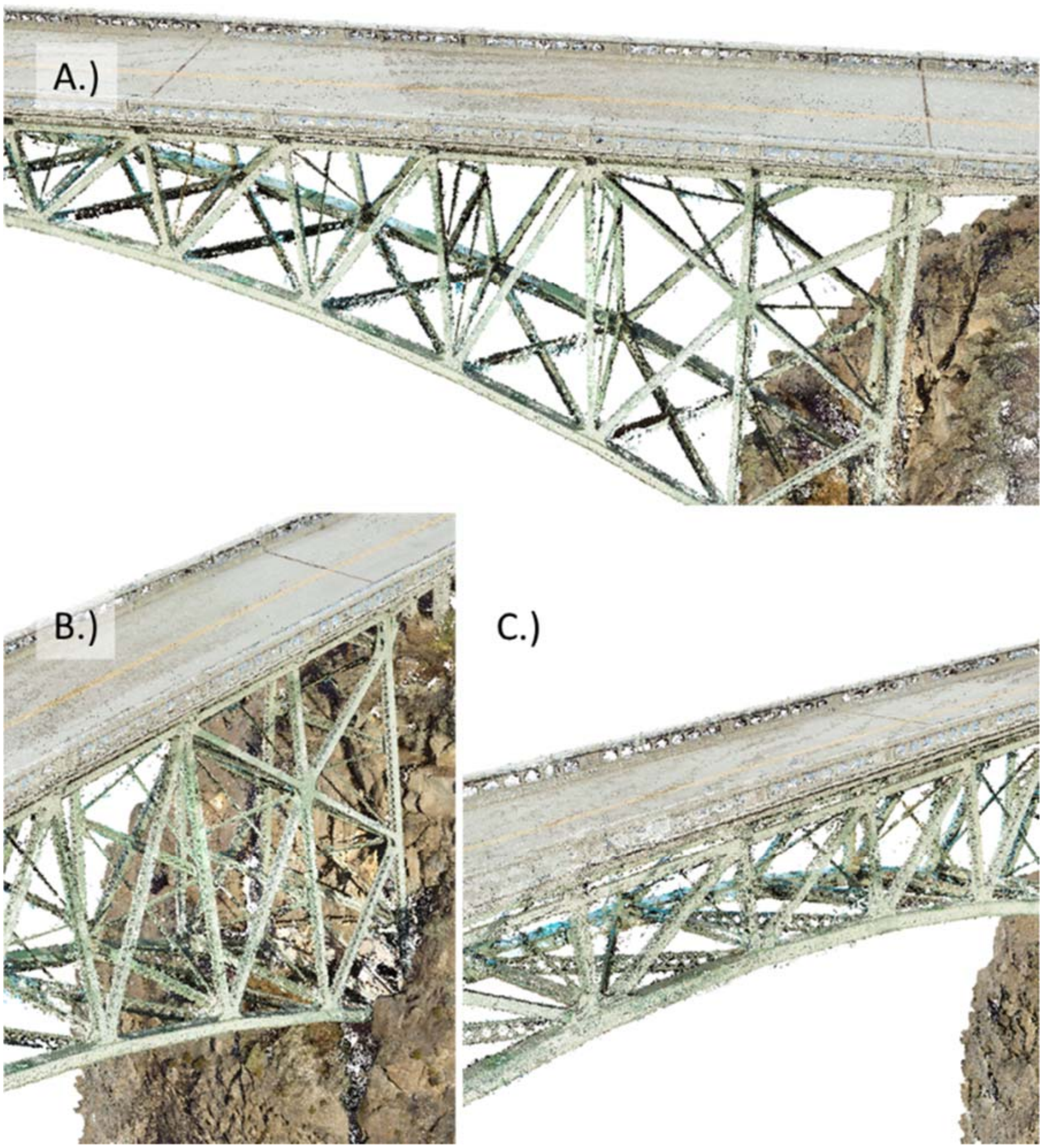

Figure 4: A.-C.) Detailed views of the Crooked River Bridge point cloud

Another benefit from creating a point cloud from the images is that it creates a database index for the images. If there is a connection of interest, the inspector can select one or more points to filter the images that the selected points appear in (See Figure 5). This feature enables the inspector to quickly look through all the photos of that region to help ensure that illumination in one photo does not obscure details that appear in other images thereby giving a more thorough inspection.

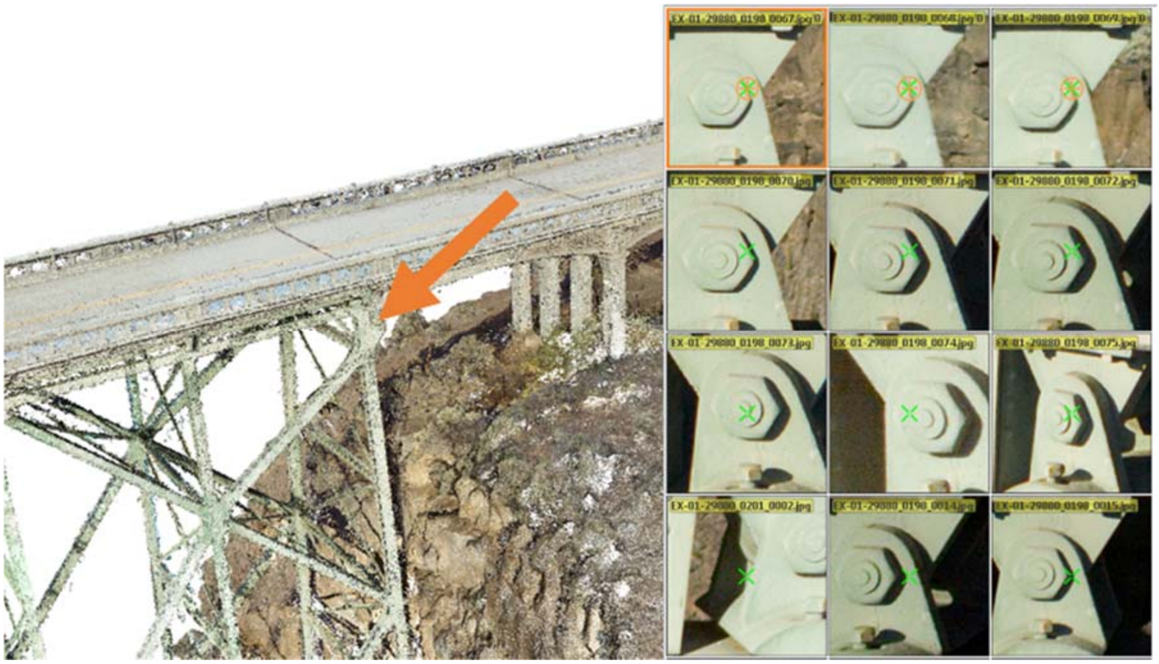

Figure 5: Example of photo index created from point selection in point cloud

Contrast enhancement (using, e.g., adaptive histogram equalization or other digital image processing techniques) can be used to improve detail in digital UAS imagery acquired under poor illumination conditions. The challenging logistics involved in operating a UAS near a bridge often result that the imagery is acquired under less than ideal illumination conditions. Fortunately, the dynamic range and bit depth of many digital cameras currently operated on UAS provide imagery suitable for a range of image processing and enhancement techniques. Examples of the types of digital image processing that can be applied to UAS imagery acquired in poor illumination conditions are illustrated in Figure 6.

Figure 6: Results of applying digital image processing techniques in MATLAB to senseFly albris imagery of Mill Creek Bridge acquired in the morning during poor illumination conditions.

The input to the histogram equalization process consisted of images acquired of Mill Creek Bridge when the bridge members being inspected were heavily shadowed. The first step consisted of applying contrast limited adaptive histogram equalization (CLAHE) to the imagery in MATLAB. Adaptive histogram equalization works by applying histogram equalization locally, based on a histogram computed for a square region surrounding each pixel in the image. Specifically, within each square region, each input pixel value is remapped to the cumulative distribution function (CDF) of pixel values within the region, evaluated at that input value.

Mathematically, this can be expressed as a mapping from the input intensity (or pixel "brightness value"), s_k, to a new value r_k (Gonzalez and Woods, 2002):

$$s_k = T(r_k) = (L-1)\sum_{j=0}^{k} \frac{n_j}{n} \quad \text{(EQ 1)}$$

where L is the number of possible intensity values (e.g., 256 in an 8-bit image), n is the total number of pixels in the sub-image, and n_k is the number of pixels with intensity value r_k. CLAHE adds an additional step of limiting amplification. Noise was then suppressed in the CLAHE output by filtering with a 2D Gaussian lowpass filter, as follows:

$$I_{lp} = h_g * I_{CLAHE} \quad \text{(EQ 2)}$$

Where $*$ is the convolution operator, and h_g is a 2D, 3x3 Gaussian lowpass filter:

$$h_g = \frac{1}{16}\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix} \quad \text{(EQ 3)}$$

The images on the right-hand side of Figure 14 illustrate the output of these digital image processing steps implemented in MATLAB. Bolt patterns and other details that were obscured by shadows are more readily discernable in the output. While this type of processing can be computationally intensive with large images and is, therefore, difficult to apply in real time during the data acquisition, it can easily be applied back in the office before a detailed visual review of the imagery by the inspector.

2.5 Data Collection

In order to demonstrate the quality of the imagery that can be acquired with a UAS, test flights were conducted along three bridges in central and western Oregon. The three subject bridges are Independence Bridge, Mill Creek Bridge, and Crooked River Bridge. The primary objective of the flights was to evaluate a variety of different flight methods and unmanned aircraft and investigate if the resulting imagery was useful as a supplement to a conventional bridge inspection. The focus of the flights was on acquisition of high-resolution imagery and video of bridge connections, bearings, joints, and other elements that are difficult to view from the ground. To search for possible erosion and scour, imagery was also collected upstream and downstream of the bridge.

2.5.1 Independence Bridge

Independence Bridge is a deck plate girder bridge over the Willamette River on River Road South, Marion County, Oregon. The Independence Bridge was originally constructed in 1951, and was rehabilitated in 1985. With a total length of 675.4 m, longest span of 46.3 m, total deck width of 7.9 m, and bridge deck area of 2,787 m^2, it was rated as a "large bridge" by the Marion County Bridge Inspection Program. Although the deck, superstructure, and substructure appear to be in good condition, the bridge is considered functionally obsolete as its design is fracture critical (i.e., failure of a steel member would cause a portion of or the entire bridge to collapse). UAS flights were conducted on September 21, 2015 with a consumer-grade DJI Phantom 3 Pro multicopter platform equipped with a gimballed camera capable of collecting 4k video and 12-megapixel photography (see Figure 7).

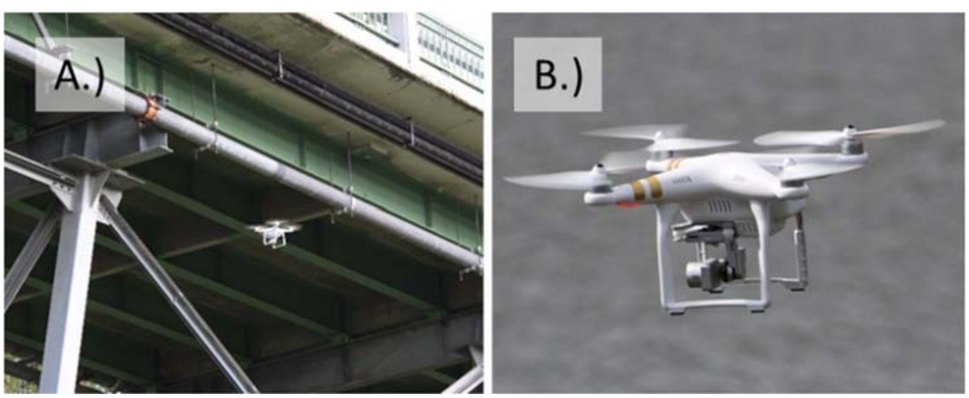

Figure 7: A.) Independence Bridge in Oregon with DJI Phantom 3 Pro Flying alongside; B.) DJI Phantom 3 Pro

The Phantom 3 Pro was not equipped with a technology for executing Waypoint-Assisted Flights, thus the pilot used the Sensor-Assisted Manual Flight method. One of the major concerns was that the Independence Bridge might block or degrade the GNSS signal. In order to choose the best time of day to fly with the least likelihood of poor GNSS signal, satellite availability plots were created along and near the upstream and downstream sides of the bridge. Figure 8 shows several points where satellite availability plots were created.

Figure 8: Independence Bridge Sky Plot Locations

To create the satellite availability plots; first, overhead obstructions were plotted at each of the points using digital surface model of the area derived from airborne lidar data. Airborne lidar data was used to build a surface model of the bridge's surroundings. Because the data is aerial based and collected at a relatively high altitude, the underside of the bridge has no data. The lack of data causes the edges of the bridge to be represented as if they were walls extending to the base of the river instead of a bridge with an open area. This would be a worst case scenario for the

UAS, as it would block any signals potential signals coming through the bridge's underside so it would be conservative assumption to use this model. To create the overhead obstruction plot, also known as sky plot, a skyline function is run in ArcMap on the point and surface model then that skyline is used to run a skyline graph function. This creates a sky plot which can be imported into a satellite availability software. These sky plots were imported into Leica Geo Office to conduct the planning. Figure 9 shows an example of the one of the worst-case positions of the tested locations.

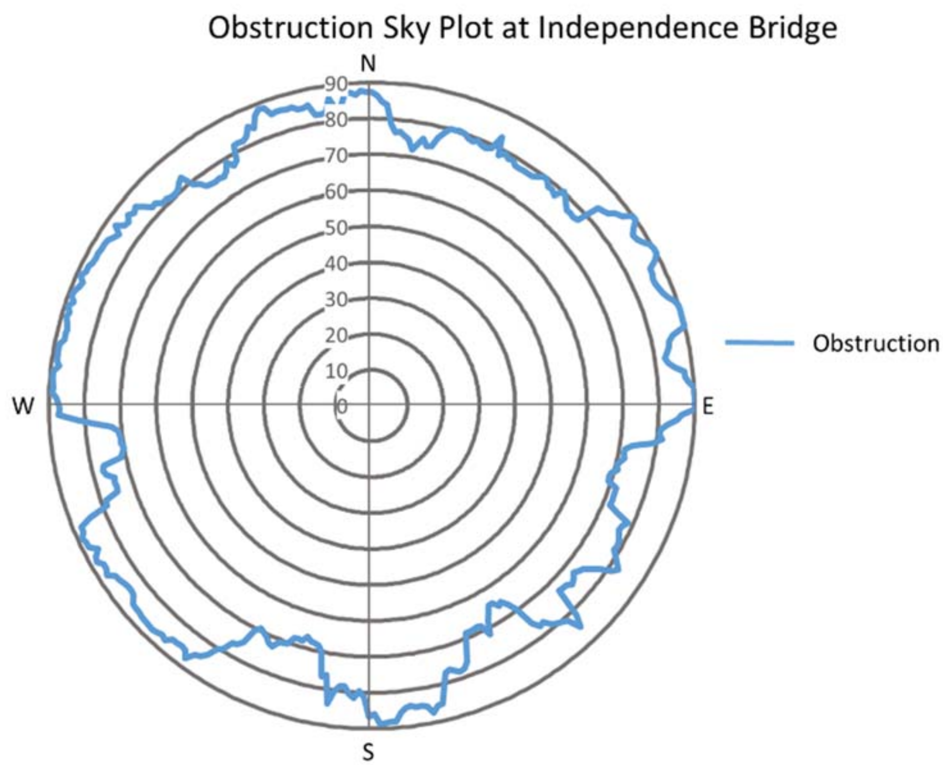

Figure 9: Sky plot at Independence Bridge created in ArcMap

After creating this sky plot for each of the positions they were imported into Leica Geo Office 8.3 (LGO) where the satellite availability was determined for September 21, 2015. Figure

10 is the chart generated by LGO that displays the number of satellites as well as the position dilution of precision (PDOP).

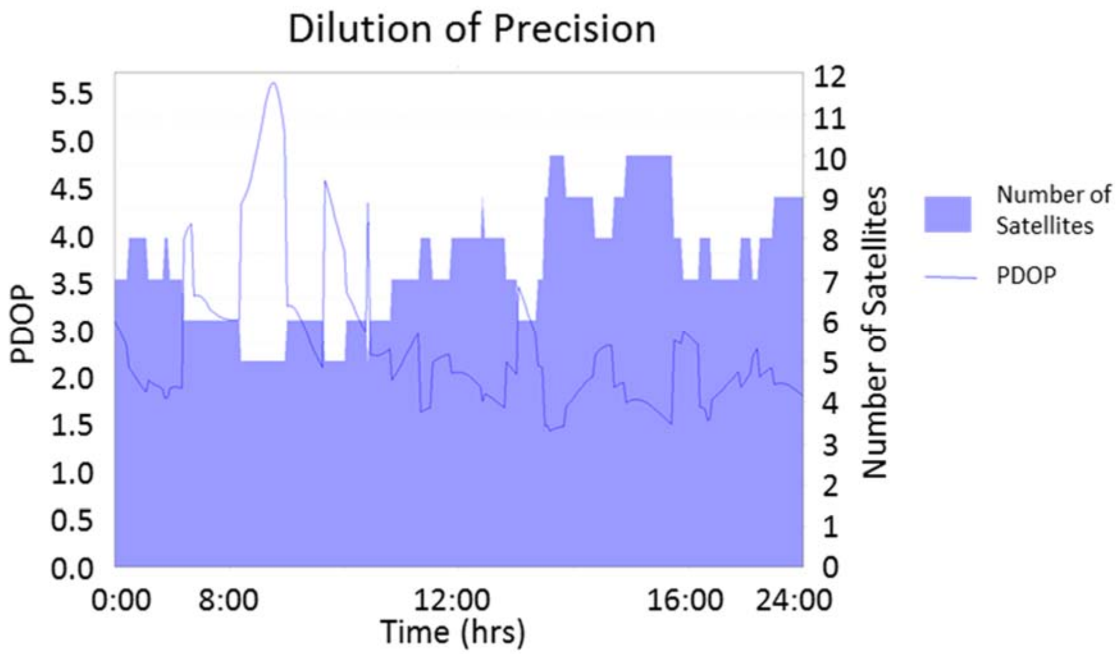

Figure 10: Position dilution of precision plot (PDOP) from Leica Geo Office

The results from this planning shows that the best time to fly would be after 9 am as there is a large spike in PDOP at 8-9 am. The spike on the plot is caused by a drop in the number of satellites that were visible at that time. The number of visible satellites during this window is only five, and they are all located roughly in the same area of the sky. In order to avoid this poor GNSS window, all operations were scheduled after 9 am.

During flight, the pilot was able to position the aircraft within 7 m of each side of the bridge, then slowly moved the aircraft in a direction parallel to the bridge. With the camera pointed at the bridge and tilted up and down using the gimbal, high-definition 4k video was captured. The camera collected 4k video that was displayed in real-time on an Apple iPad Mini tablet mounted on top of the remote controller.

2.5.2 Mill Creek Bridge

Mill Creek Bridge is located on the Warm Springs Reservation in central Oregon. It is a Cantilevered Warren deck steel truss bridge that has a total length of 163 m and three spans (See Figure 11). Originally constructed in 1948 and reconstructed in 2002, the bridge is located on US highway 26 and crosses a 100 m deep gorge.

Figure 11: Mill Creek Bridge, Warm Springs Reservation

Flights were performed on July 14, 2016, with a senseFly albris multicopter platform equipped with multiple sensors designed to assist with structural inspections. This small multicopter is capable of all three flight methods presented in this paper. It is equipped with five wide-angle cameras (i.e., “navcams”) and five ultrasonic sensors that detect objects up to five meters away from the unmanned aircraft. In addition to these sensors the primary sensors include an HD video camera, 38 megapixel still camera, and thermal infrared camera. These main sensors are installed on a front-mounted gimballed camera head that can be rotated in flight 180° from nadir to zenith (or any desired angle in between), enabling data to be captured on the underside of objects. Figure 12 shows the layout of these sensors and their orientation on the aircraft.

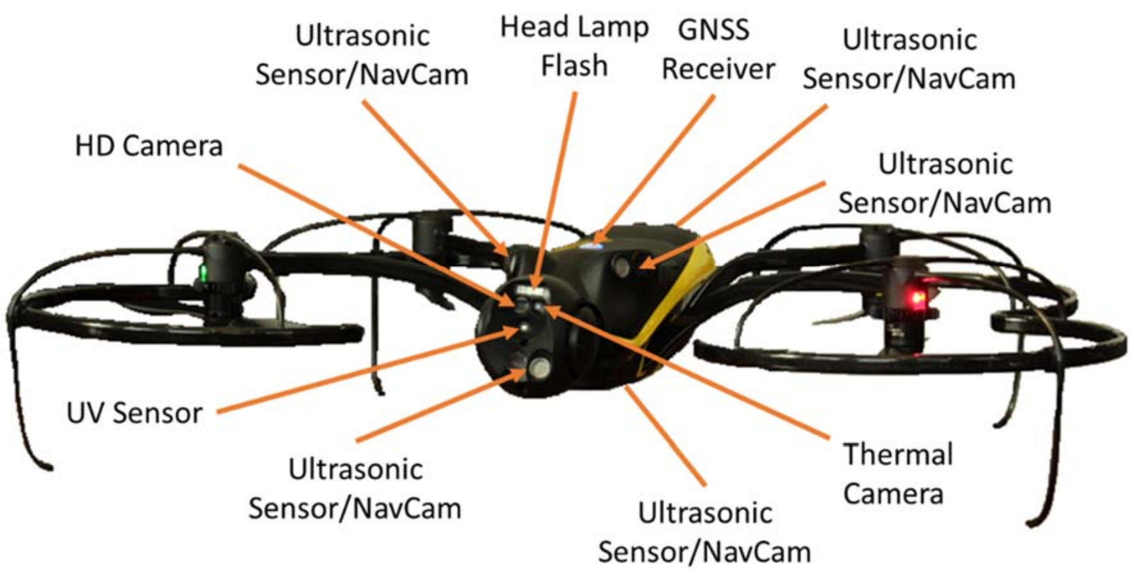

Figure 12: Orientation of Cameras, Navcams, and ultrasonic on the albris for assisting the operator during operations

The flights were performed by flying alongside the bridge with the aircraft being perpendicular to the bridge to gather as much high of resolution imagery as possible. The aircraft utilized the GNSS aided manual flight mode as well as the ultrasonic proximity sensors to keep a 5 m standoff from the bridge. Angles displaying the underside of the bridge as well as structural members in difficult to access locations were photographed while using this technique.

2.5.3 Crooked River Bridge

Crooked River Bridge was constructed so that highway US 97 could cross the Crooked River gorge. It is a steel arch bridge having a total length of 141 m and a main span of 100 m (See Figure 13). It is situated 90 m above the gorge base and was completed in 1926. However, to accommodate the increasing traffic on US 97 a new, wider bridge was built, the Rex T. Barber Veterans Memorial Bridge, completed in 2000. The Crooked River Bridge was then repurposed as a pedestrian bridge at Peter Skene Ogden State Park.

Figure 13: Crooked River Pedestrian Bridge

Flights were performed on July 13, 2016 with the senseFly albris multicopter. The objective of the Crooked River Bridge was to not only gather imagery that would prove useful for inspections but also to gather enough imagery to create a 3D model. The approach to accomplish this was to make use of both Waypoint-Assisted flights and Sensor-assisted flights.

The Waypoint-assisted flights were planned for overhead flights at 40 m above the bridge deck with 80 percent image overlap. A back-and-forth (lawnmower) flight plan was created with the camera set to collect nadir images, similar to those that would be collected for creating an orthophoto and SfM-derived point clouds.

The Sensor-assisted flights were performed alongside the bridge making use of the five ultra-sonic sensors to keep a close standoff distance (approximately 5 m) from the bridge. The ultra-sonic sensors with a constant strafing flying speed helped to acquire high-resolution imagery from a viewing angle only possible if a conventional inspection were performed with a snooper crane or using climbers.

2.6 Results and Discussion

2.6.1 Sample Images

Approximately 600 still images were successfully collected of each bridge, and this paper presents some of them (Figure 14 and 15). Cracks in concrete, fracture-critical connections, hardware, and bearing locations were all identifiable in the imagery. In addition, unique angles of the banks of the rivers, paint failures, and rusted pins could be viewed in real time on the FPV monitor. All of these inventory items and defects could be documented remotely using UAS.

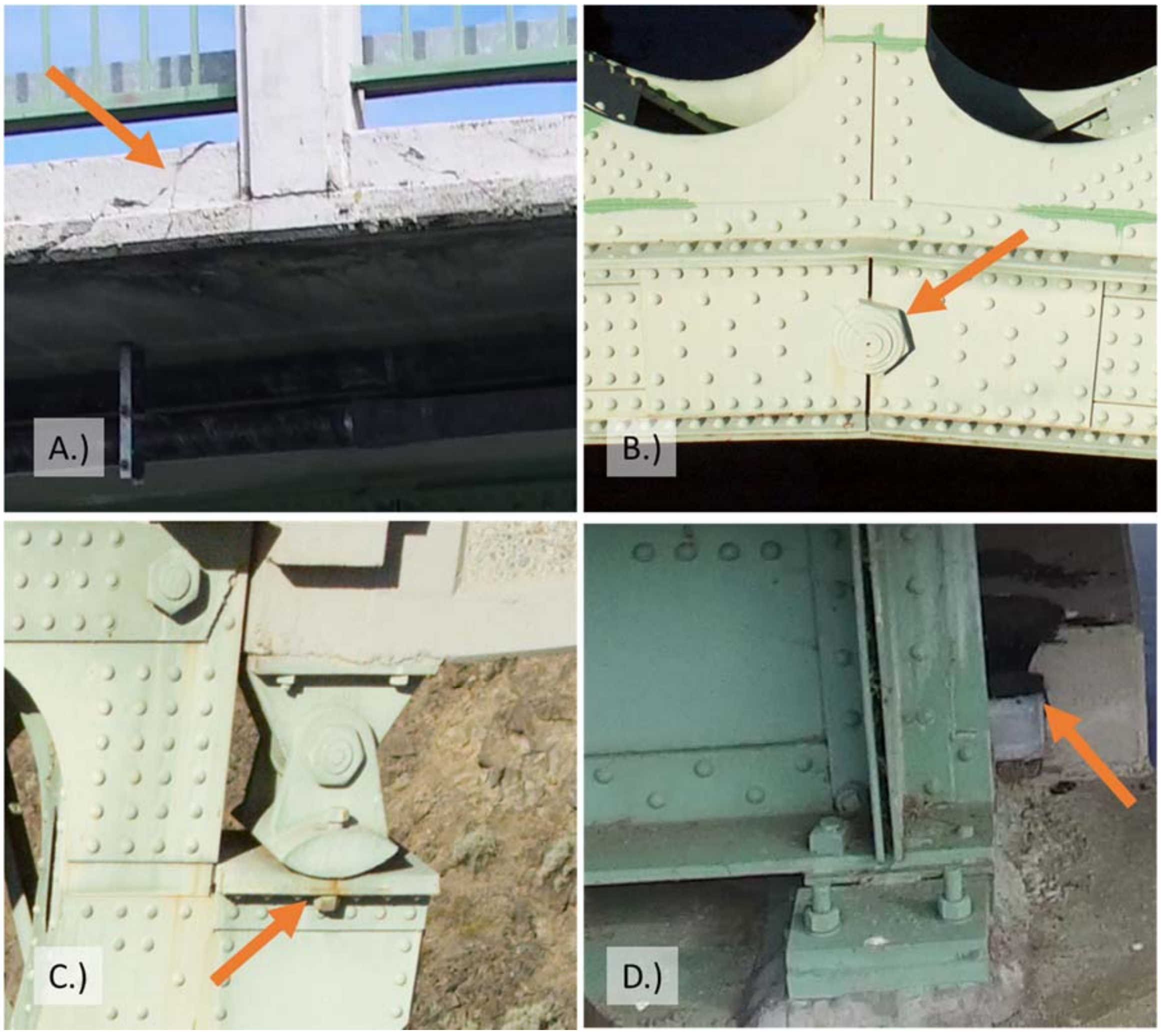

Figure 14: A.) Concrete railing cracking not visible from the bridge deck B.) Large center bolt and gusset plate C.) Concrete bearing on steel and large steel bolts some rust visible D.) Steel bearing on concrete pier with possible tar leaking through a joint

Figure 15: A.) Paint failure with exposed rust on bearing structure B.) Aerial image of bank upstream of river C.) Under side view of pin connections on a bridge D.) Connection pin with signs of rust.

2.6.2 Capabilities for UAS Bridge Inspection

The results of the three UAS bridge inspections, as well as a detailed review of UAS and payload specifications, were used to assess, item-by-item, which required reporting elements and types of bridge inspections can or cannot be aided by a UAS. A rating system on a 1-4 scale was used to designated the usefulness of a UAS for each listed item; where 1 = Not Useful, 2 = Limited

Use, 3 = Useful, and 4 = Very Useful. The results of this assessment are summarized in Tables 3-6.

Table 3: Bridge Report Inventory Items UAS Can Facilitate

Report Requirement	Rating (1-4)	How it can aids or why it cannot
Identification	1	This information will be known prior to any field inspection with a UAS.
Structure Type and Material	3	High Resolution photos of the structure can display the type and the material of the bridge.
Age and Service	2	The age of the bridge can only be estimated from imagery collected by a UAS; however, the surrounding area can be recorded by a UAS
Geometric Data	4	Previous records of geometric values can be compared with geometries acquired from 3D reconstructions of the imagery collected during a UAS inspection
Navigation Data	3	Many forms of pier protection could be identified and waterway clearances can be measured from point clouds generated from 3D reconstructions of UAS imagery.
Classification	1	This information should be known prior to any field inspection. UAS flights are not needed for determining the facility that is using the bridge.
Load Rating and Posting	2	This would be better performed by the engineer on the ground. Signage is easily accessible from the ground.
Proposed Improvements	2	This is a section written up by the engineer on how to improve the bridge condition. However, the imagery provided could aid the engineer in assessing the bridge.
Inspections	1	This section refers to previous inspections performed. This data would be recorded previously.

Table 4: Bridge Report Condition Ratings UAS Can Facilitate

Report Requirement	Rating (1-4)	How it can aids or why it cannot
Deck	4	Geometry of Deck as well as presence of defects could be identified via high resolution imagery
Superstructure	4	Presence of cracks and other defects can be identified as well as monitored though imagery collected from regular UAS flights over time
Substructure	4	Presence of cracks and other defects can be identified as well as monitored though imagery collected from regular UAS flights
Channel and Channel Protection	3	Hydraulic countermeasures could be visually monitored by regular inspection by a UAS. The bank conditions can be monitored through low altitude flights.
Culvert	3	Any exterior blockage of culverts that are not entirely submerged can be identified by a UAS

Table 5: Bridge Report Appraisal Items UAS Can Facilitate

Report Requirement	Rating (1-4)	How it aids or why it cannot
Structural Evaluation	4	Presence of cracks and other defects can be visually identified as well as monitored though imagery collected from regular UAS flights
Deck Geometry	4	The geometry of the deck can be recorded in imagery with proper ground control
Under-Clearances	4	Clearance values and opening can be potentially measured by 3D reconstructions of the UAS imagery
Waterway Adequacy	3	Waterway openings can be recording and captured with high resolution photography from a UAS
Approach Roadway Alignment	4	The alignment of the bridge roadway access can be recreated via low altitude flights; orthophotos can be generated from reconstructions of the UAS imagery
Traffic Safety Features	3	A UAS can provide views of the outer side of bridge railings
Scour Critical Bridges	2	As probing is not currently possible with a typical UAS, testing for scour is not possible; however, bank monitoring from regular inspection is possible with aerial imagery

Table 6: Bridge Inspection Types UAS Can Facilitate

Bridge Inspection Type	Rating (1-4)	How it aids or why it cannot
Initial	4	The visual base line can be set using the imagery collected by the UAS
Routine	4	Being a primarily visual inspection using UAS can greatly decrease the amount of time a bucket truck or climber would need to be used
Damage	2	Depending on the level of damage UAS can help identify where the damage occurred and document the visual defects
In-depth	2	The amount of use of bucket trucks can be decreased. However, this inspection requires more physical tests so an inspector needs to be able to touch the bridge
Fracture-critical	2	The amount of use of bucket trucks can be decreased. However, this inspection requires more physical tests so an inspector needs to be able to touch the bridge
Underwater	1	The UAS presented in this paper are flying systems that offer very little to underwater operations. Most are not water proof.
Routine Wading	2	Bank inspections can be surveyed in ways not previously done for points of view that an inspector couldn't normally get. However, most operations wouldn't require UAS
Special Inspections	1-4	The level of usefulness is dependent on how the special inspection is set up. Depending on the inspection it could be very useful or not useful.

2.6.3 Challenges for UAS Bridge Inspection

The results of the testing were encouraging for implementing UAS into bridge inspections. Nevertheless, there are still several challenges that exist that need to be addressed for this technology to be fully optimal for bridge inspections. Four related challenges were identified after performing the tests: (1) Image resolution; (2) Standoff distance and pilot comfort; (3) Poor lighting; and (4) Lack of cleaning.

Image Resolution

An important criterion in evaluating the capabilities of UAS for inspections is whether they can provide comparable results to a physical inspection. Although the use of a UAS seems viable for visual and routine bridge inspections, some of the more in-depth bridge inspections (e.g., inspections for fracture-critical, or functionally obsolete bridges), as prescribed by the Bridge Inspector's Reference Manual require the inspector to be within "arm's length" of the structural member (Ryan 2008). The visual resolution of "arm's length" for a typical human inspector can be determined and potentially replicated with still imagery. Determining the spatial resolution of typical human with 20/20 vision at arm's reach is not a trivial task, due to a large number of variables including: refractive error, size of the pupil, illumination, time of exposure of the target, area of the retina stimulated, state of adaptation of the eye, and eye movement (Kalloniatis and Luu 2005). A study done by Blackwell (1946) defines the human eye's resolution as function of brightness and contrast. In bright light, Blackwell (1946) estimated the resolution as 0.7 arc-minutes. This value is comparable to values derived by more complicated means (e.g.,Kalloniatis and Luu 2005), and 0.7 arc-minutes was assumed for this study..

The resolution of the images collected by the UAS for inspection purposes needs to be sufficiently high to satisfy the "arm's reach" requirement of the bridge inspector's manual. To highlight this difficulty, the spatial resolution of the human eye was calculated from its angular resolution (0.7 arcminutes) at an average arm's length (63.5 cm). For small angles, the following simple relationship is applied:

$$S = R\theta \qquad \text{(EQ 4)}$$

Where S = the distance subtended at the standoff distance R by an arc of θ in radians. Setting R= 635 mm and θ= 0.2 mrad (0.7 arcmin), the spatial resolution of a human eye at arm's length is approximately 0.13 mm. Capturing imagery at this resolution is difficult with the consumer-grade cameras that are typically mounted on small UAS. It forces the operator to fly the aircraft in close proximity to the bridge to accomplish this resolution. The associated standoff distance to acquire images at this level of detail can be calculated from the following relationship:

$$S = \frac{SW \cdot R}{f \cdot PW} \qquad \text{(EQ 5)}$$

where *SW* = sensor width (physical dimension in mm), *R* = standoff distance, *f* = focal length in mm, *PW* = the width of the image in pixels, and *S* is the distance in mm between adjacent pixels on the structure being imaged, directly analogous to the so-called ground sample distance (GSD) in photogrammetry and remote sensing. Table 7 shows three different camera's intrinsic parameters and the resulting standoff distance to achieve the 0.129 mm.

Table 7: Camera Intrinsic Parameter Values and Resolution

Camera Model	Sensor Width (mm)	Fixed Focal Length (mm)	Image Width (pix)	Field of View Width (m)	Standoff Distance for 0.129 mm resolution (m)	Resolution at 5m (mm/pix)
Sensefly Albris HD Camera	9.90	8.0	7152	0.923	0.746	0.865
Sony a5000	23.20	16.0	5456	0.704	0.485	1.329
Sony WX 500	6.17	4.1	4896	0.632	0.420	1.537

To achieve this level of detail with the camera on senseFly albris the standoff distance from the subject would have to be 0.75 m. It is unrealistic for a pilot to feel comfortable flying this close to a solid object trying to image it and obtain good coverage. Using a camera with a larger sensor size and that is capable of a 3x optical zoom, the Sony a5000 would need to be 1.5 m from the object to get the same resolution of the eye. Higher quality cameras could improve this issue as well as the addition of a larger optical zoom.

Standoff Distance

Flying in close proximity to a structure is uncomfortable for even the most experienced pilots. Winds can be unpredictable around bridges. Eddies and thermals are not uncommon near the bridge and can cause the aircraft to be pushed toward or away from the bridge. This unpredictable movement is stressful. To prevent the aircraft from contacting the bridge a standoff distance of five meters is recommended to provide time to react to the movement as well as feel comfortable during the flight.

Poor Lighting

Capturing images of areas that have members densely packed can be problematic for several reasons. If there is not space to position the UAS safely the desired angle might not be possible. Also, illumination becomes an issue if sunlight is blocked and the area desired to be photographed is too dark. (See Figure 16) Illumination changes throughout the day as a function of solar azimuth and elevation angles and cloud cover, as well as shadowing from different parts of the structure itself. High beam flash, external lighting and/or contrast enhancement (as described above) are all means of alleviating this problem. However, illumination conditions during the flight are a critical factor that should be considered in planning and throughout a UAS bridge inspection project.

Figure 16: A.) Steel bearing on rock anchor in canyon B.) Rust build up on support structure for bridge deck C.) View of soffit of steel truss bridge D.) Inside view of connection bearing location of a steel truss bridge

Lack of Brushing/Cleaning

Another issue that comes up with UAS based inspections is the inability to contact the bridge. There may be rust, dirt, or guano covering potential cracks that could be identified using a wire brush if someone were on the structure to clean to see underneath. (Figure 15) The inability of UAS to clean the members of the bridge to detect obscured defects on the bridge is a shortcoming of the technology.

2.7 Conclusions

Three UAS bridge inspections conducted in this paper clearly highlight both the benefits and challenges associated with operational use of UAS for bridge inspection using current technology. Defects such as cracks, pack rust, loose and missing hardware were easily identifiable in the imagery of Independence Bridge, Crooked River Bridge, and Mill Creek Bridge. Nearly all aspects of the visual based inspection can be satisfied if adequate space for maneuverability and lighting is available around the bridge.

Inventories and models were generated from the imagery and video and were used for additional types of analysis back in the office, extending well beyond what can be done in the field. Georeferenced 3D point clouds and other 3D models generated from the imagery enabled precise geometric measurements. Adaptive contrast enhancement showed potential for improving the level of detail that could be discerned in imagery acquired under relatively poor illumination conditions. These findings support the conclusion that UAS can augment the bridge inspector's tool set.

At the same time, another key finding is that, while the imagery acquired with a UAS typically provides the inspection with much more information than can be obtained visually while standing on the deck or one of the ends of the bridge, the resolution of the imagery collected does not currently provide level of detail that the bridge inspector could obtain visually if he/she were climbing on the bridge. Additional challenges noted in this work include: 1) the limitations of a lack of optical zoom on some UAS payloads, requiring the pilot to operate uncomfortably close to the structure to acquire imagery of roughly comparable resolution to what could be obtained visually at arm's-length, 2) the need to consider illumination conditions, even if the imagery will be post-processed, 3) the limitations of current flight planning software for inspections, which can determine standoff distance as a function or user-specified resolution, but not the reverse, and 4) wind and other environmental challenges.

This study also led to several recommendations for further research and development in UAS bridge inspection. A detailed cost benefit analysis was beyond the scope of this study, but would be highly beneficial for federal and state transportation departments (DOTs) considering using UAS technology. Flight planning for UAS structural inspections is another recommended topic for additional research and development. Inspections would be greatly facilitated by improving the options for waypoint missions. Camera enhancements, including optical zoom, are another recommended avenue of research. Further work on these topics will enable UAS to be used to their full potential in bridge inspections and pave the way for increasing operational use by bridge inspectors.

2.8 Acknowledgements

The author would like to acknowledge Oregon Department of Transportation and PacTrans for their sage advice as well as for funding this project. Without their help the study would not have been possible or successful. Also the assistance from VDOS and Complier Enterprise in planning and gaining authorization for operations was vital to the project. Lastly a special thanks to students from Oregon State University, Farid Javadnedjad, Chase Simpson, and Jonathan Burnett for their assistance in gathering the data presented in the paper.

2.9 References

American Association of State Highway and Transportation Officials (AASHTO) (2011). *The Manual For Bridge Evaluation Second Edition*.

Adams, S., M. Levitan, and C. Friedland (2014). "High Resolution Imagery Collection for Post-Disaster Studies Utilizing Unmanned Aircraft Systems (UAS)." Photogrammetric Engineering & Remote Sensing 80.12: 1161-1168.

Agisoft (2016). “Agisoft PhotoScan User Manual: Professional Edition, Version 1.2” Agisoft LLC. 103 pp.

Blackwell, H.R. (1946). “Contrast Thresholds of the Human Eye”. J. of the Optical Society of America. 36(11), 624-643

Brooks C., Dobson R., Banach D., Dean D., Oommen T., Wolf R., Havens T., Ahlborn T., and Hart B. (2015). Evaluating the Use of Unmanned Aerial Vehicles for Transportation Purposes., Michigan Tech Research Institute, Ann Arbor, Michigan.

Ellenberg A., L. Branco, A. Krick, I. Baroli, and A. Kontsos (2014). “Use of Unmanned Aerial Vehicle for Quantitative Infrastructure Evaluation.” J. Infrastruct. Syst., ASCE.

Eltner, A., Kaiser, A., Castillo, C., Rock, G., Neugirg, F., and Abellán, A. (2016). “Image-based surface reconstruction in geomorphometry - merits, limits and developments.” *Earth Surface Dynamics*, 4(2), 359–389.

Eschmann C., C.-M. Kuo, C.-H. Kuo, and C. Boller (2013). “High-Resolution Multisensor Infrastructure Inspection with Unmanned Aircraft Systems.” International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. 1(2), 125-129.

Federal Aviation Administration (FAA), (2015). "Fact Sheet – Unmanned Aircraft Systems (UAS)." FAA, < https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=14153 > (last date accessed: 3 Dec 2015).

Federal Aviation Administration (FAA), (2016). Public Operations (Governmental): <http://www.faa.gov/uas/public_operations> (last date accessed: 27 May 2016).

Furukawa, Y., and Ponce, J. (2010). "Accurate, Dense, and Robust Multiview Stereopsis." *IEEE Transactions on Pattern Analysis and Machine Intelligence*, IEEE, 32(8), 1362–1376.

Gillins, M.N., Gillins, D.T., and Parrish, C., (2016). Cost-Effective Bridge Safety Inspection using Unmanned Aircraft Systems (UAS). Proceedings of Geotechnical and Structural Engineering Congress 2016, ASCE, Phoenix, A, 10 pp.

Hallermann N., and Morgenthal G. (2013). "Unmanned Aerial Vehicles (UAV) for the Assessment of Existing Structures." IABSE Symposium Report. IABSE 101(14).

Hallermann N., Morgenthal G., and Rodehorst V. (2014). "Vision-Based deformation monitoring of large scale structures using Unmanned Aerial Systems." IABSE Symposium Report, IABSE.

Hugenholtz, C., Walker, J., Brown, O., and Myshak, S., (2014). Earthwork Volumetrics with an Unmanned Aerial Vehicle and Softcopy Photogrammetry, J. Surv. Eng., 10.1061/(ASCE)SU.1943-5428.0000138, 06014003.

Kalloniatis M., and Luu, C. (2005). Webvision: The Organization of the Retina and Visual System [Internet]. Salt Lake City (UT): University of Utah Health Sciences Center.

Khan F., Ellenberg A., Mazzotti M., Kontosos A., Moon F. Pradhan A., and Bartoli I. (2015). "Investigation on Bridge Assessment Using Unmanned Aerial Systems." Structures Congress 2015.

Lee, S., and Choi, Y. (2015). “Topographic Survey at Small-scale Open-pit Mines using a Popular Rotary-wing Unmanned Aerial Vehicle (Drone).” *Tunnel and Underground Space, Korean Society for Rock Mechanics*, 25(5), 462–469.

Otero L., Gagliardo N., Dalli D., Huang W-H., and Cosentino P. (2015). “Proof of Concept for Using Unmanned Aerial Vehicles for High Mast Pole and Bridge Inspections”, Florida Institute of Technology, Department of Engineering Systems, Melbourne, Florida.

Pajares, G., (2015). Overview and Current Status of Remote Sensing Applications Based on Unmanned Aerial Vehicles (UAVs). Photogrammetric Engineering & Remote Sensing, ASPRS, 81(4): 281-329.

Remondino F., Barazzetti L., Nex F., Scaioni M., and Sarazzi D. (2011) "UAV photogrammetry for mapping and 3d modeling–current status and future perspectives." International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 38.1: C22.

Ryan, T.W., Mann, J. E., Chill Z. M., Ott B. T. (2008). “Bridge Inspector’s Reference Manual (BIRM).” 984 pp.

Sa I., S. Hrabar, and P. Corke (2015). “Outdoor Flight Testing of a Pole Inspection UAV incorporation High-Speed Vision.” Field and Service Robotics, 105(3) 107-121.

Snavely, N., Seitz, S. M., and Szeliski, R. (2006). “Photo tourism.” *ACM SIGGRAPH 2006 Papers on - SIGGRAPH ’06*, ACM Press, New York, New York, USA, 835.

Vaghefi K., Oats R., Harris D., Ahlborn T., Brooks C., Endsley K., Roussi C., Shuchman R., Burns J., and Dobson R. (2012). “Evaluation of Commercially Available Remote Sensors for Highway Bridge Condition Assessment.” Journal of Bridge Engineering, 17(6), 886-895.

Wood R. L., Gillins D. T., Mohammadi M. E., Javadnejad F., Tahami H., Gillins M. N., and Liao Y. (2017). “2015 Gorkha Post-Earthquake Reconnaissance of a Historic Village with

Micro Unmanned Aerial Systems." 16th World Conference on Earthquake (16WCEE), Santiago, Chile (In-Press).

3.0 Appendix A

In addition to the three bridges, a slightly modified methodology was used to inspect a wireless communications tower. The tower is similar to bridges in that it is to access unless the inspector is directly climbing on the structure. Connections need to be tight and damage free for the tower to be fully operational. Using UAS technology an inspector can view these connections remotely.

3.1 Washburn Butte Communication Tower

Washburn Butte, located approximately 6 km north of Brownsville Oregon, has 5 different communication towers on its highest point. The towers range in size as well as type and shape on the site. The easternmost tower was chosen for inspection as it had the most interesting features on its “A-Frame with a square base”. (See Figure 1A) The tower is 48.8 m tall and has 8 antennas installed at various heights with different orientations on the frame.

Figure 1A: Washburn Butte Communication Towers

Flights around the Washburn Butte were a combination of overhead mapping flights and a cylindrical flight plans. The flight plans however did not allow for the highest resolution imagery possible due to the flight planning software. The imagery, however, was collected fully without the operator having to give direct commands.

From the photographs gathered an inspector can identify cracks in concrete, ensure hardware is in place and fastened, and also view bearing and connections in difficult to access areas (see Figure 2A).

Figure 2A: A.) Side view of Microwave Antenna and its connection to the Washburn Butte Tower B.) Back view of a Microwave Antenna and its connection to the Washburn Butte Tower C.) Loose bolt on tower frame connection D.) Antenna and its connection to the tower.

If enough care is taken during the collection of imagery Structure from Motion (SfM) algorithms can be applied to create a three dimensional to scale point cloud of the structure and site (See Figures 3A).

Figure 3A: Point Cloud of Washburn Butte and its 5 towers. Point cloud is georeferenced.