COST-EFFECTIVE BRIDGE SAFETY INSPECTIONS USING UNMANNED AERIAL VEHICLES (UAVS)

FINAL PROJECT REPORT

by

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16. Abstract

This report presents the results of a study on the use of unmanned aircraft systems (UAS) in bridge inspections. A detailed literature review was conducted to assess and document the current state of knowledge on the use of UAS in structural inspections and related engineering applications. A particular focus was on related work done by various state DOTs. Given the technical specifications and findings documented in the literature review, an item-by -item review of bridge inspection manuals was then performed to assess which elements of a bridge inspection could potentially benefit from use of UAS. Additionally, various categories of UAS and payloads were evaluated for bridge inspection. A small multicopter UAS was acquired and used to collect ultra-high-definition video and still imagery of a large bridge in Independence, Oregon. The imagery was reviewed by project team members and ODOT bridge inspectors. The results of the Independence Bridge inspection are presented, along with recommendations for further work. The study identified several challenges on the use of UAS for bridge inspection, including the need to capture very high resolution imagery, and problems due to strong wind and poor lighting conditions.

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List of Abbreviations

FAA: Federal Aviation Administration
FPV: First Person View
GCS: Ground Control Station
GNSS: Global Navigation Satellite System
PacTrans: Pacific Northwest Transportation Consortium
UAS: Unmanned Aircraft System
WSDOT: Washington State Department of Transportation

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Executive Summary

The Federal Highway Administration (FHWA) mandates that states visually inspect and inventory federal-aid highway system bridges once every two years (23 CFR Part 650). These mandatory inspections are critical for evaluating the safety of a bridge; however, inspections can be dangerous and costly. The purpose of this study is to investigate the use of unmanned aircraft systems (UAS) technology as a tool for assisting with a bridge inspection. UAS could be used to remotely capture imagery of a bridge and could reduce the need for climbing or for placing inspectors in platform trucks, snooper cranes, or other under-bridge inspection vehicles.

UAS are attractive technology for inspecting structures because they carry cameras that can be used to acquire close-up, high resolution still imagery and video from multiple viewing angles. Most UAS are equipped with a camera that broadcasts live video to a monitor in front of the operator. The live video assists the operator with safely positioning the aircraft during flight, and it helps ensure that imagery of specific features of the bridge are captured. Other sensors may also be available on the aircraft for assisting with the flights, such as global navigation satellite systems (GNSS) sensors, ultrasonic sensor(s), barometers, and inertial measurement unit(s). Other basic components of a UAS include the aircraft, navigation system, data link, payload (e.g., gimbal and camera), ground control station (e.g., laptop with mission planning software and/or a radio frequency controller), and human operators.

Technically, any vehicle that flies without a human onboard is defined as an unmanned aircraft. This broad definition covers a wide range of vehicles, but most civilian applications involve the use of systems that weigh less than 25 kg (55 lbs), a weight class designated by the Federal Aviation Administration (FAA) for small UAS (sUAS). Most sUAS are fixed-wing gliders, multicopters (e.g., quadcopter, hexacopter), or single-rotor helicopters. Multicopters are well suited for inspections because they are highly maneuverable, capable of hovering in place during flight, and can execute vertical take-offs and landings. Hovering enables the operator to zoom, point, and shoot the onboard camera during flight.

UAS have potential for a large number of applications, and over a dozen state departments of transportation (DOTs) have published reports on the use of UAS for alleviating transportation engineering-related problems. Several states have reported the use of UAS for monitoring traffic, inspecting construction sites, surveying and mapping, conducting roadside condition surveys, collecting aerial imagery, and inspecting structures.

UAS appear to be a particularly useful tool for performing initial and routine bridge inspections, which are primarily done visually as per AASHTO’s Bridge Inspection Manual (AASHTO, 2011). However, for in-depth bridge inspections, the AASHTO Manual requires the inspector to be at arm’s length from the bridge. Of course, a UAS cannot satisfy this requirement; however, imagery collected with a UAS can be somewhat close to the same resolution as the human eye at arm’s length. UAS also cannot be used to probe and scrape the bridge, as required for some types of in-depth inspections.

In addition to reviewing the status of UAS technology, published literature, and bridge inspection manuals, a small quadcopter was acquired to capture imagery of a large bridge in

Independence, Oregon. The purpose of the experiment was to investigate whether imagery collected from the UAS was useful for an inspection, and to investigate the capabilities and limitations of the technology. The quadcopter was successfully flown within 3 to 5 meters of the bridge, and over 55 minutes of ultra-high-definition video were recorded. The primary aim was to capture video of the joints, connections, and bearings of the bridge as well as the upstream and downstream banks. After the flights, a bridge inspector from the Oregon Department of Transportation reviewed and commented on the quality of the video.

Several minor bridge defects were identifiable in the video that would be useful for an inspection, such as evidence of a leaking joint, rust on connection bolts, concrete cracks and spalling, missing bolt nuts, and efflorescence. Example imagery of these defects are presented in the report. Additional imagery shows the condition of the banks of the river near the bridge.

Some challenges were noted worth future research and development. For instance, at times, the bridge inspector asked if even higher-resolution imagery could be collected. Unfortunately, capturing imagery with the same resolution as the human eye at arm's length is difficult. The human eye at arm's length has a rough spatial resolution of 0.1 mm. Even at a standoff distance of only 3 meters, the spatial resolution of the camera on the UAS was only approximately 0.7 mm. Flying so close to the structure is also problematic because GNSS signals are degraded or obstructed, and complicated wind eddies near the bridge could potentially push the aircraft into the bridge. A heavier aircraft is recommended because it could carry a camera with a larger sensor size and is better for flying in windy conditions. In addition, a camera with an optical zoom lens would be useful for collecting detailed imagery without the need to fly so close to the structure. Another challenge is that many bridge features are in a natural shadow or other poor lighting conditions. Natural lighting can cause over- or under-exposed imagery that is not useful for evaluating the bridge. It’s recommended to develop a system that will allow the operator to change the camera’s aperture size and exposure in real time for poor lighting. Further, tools for post-processing imagery should also be explored.

Chapter 1 Introduction

Bridges present significant challenges to highway workers around the world. They are the most common way to transport people across dangerous and difficult terrain and, hence, are vital to the transportation infrastructure. However, the American Society of Civil Engineers (ASCE) reports that one in nine of the nation's bridges are rated as structurally deficient, with an average age of 42 years (ASCE 2013). The risk associated with crossing deficient bridges spurred the Federal Highway Administration (FHWA) to mandate that states visually inspect and inventory federal-aid highway system bridges once every two years (23 CFR Part 650). These mandatory biennial bridge inspections are important for assessing the safety of a bridge. However, these inspections can be dangerous for the inspector and for the driver. Inspectors are often required to stand in platform trucks, bucket trucks (i.e., snooper cranes), or under-bridge inspection vehicles in order to access and view necessary bridge elements. Mobilizing such vehicles to bridges can be costly. Also, some inspections require extensive climbing by certified climbers, 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.

Small unmanned aircraft systems (UAS) have great potential for overcoming or alleviating some of these challenges. Because of their high maneuverability, small UAS can be used to remotely acquire close-up, high resolution still and video imagery of structures from multiple viewing angles. UAS can collect data at locations on a structure that are difficult to physically access, enabling an inspector to remotely view bridge elements while keeping both feet firmly on the ground. During flights, many UAS broadcast live video from a camera to a monitor or set of head goggles, enabling the inspector to virtually analyze the acquired imagery in real time during flight. This technology is referred to as *first-person view*. In addition, UAS can be flown frequently at a low cost in order to monitor changes on a structure over time.

Given the potential benefits, some researchers have begun exploring the use of UAS for inspecting structures or for structural health monitoring. Eschmann et al. (2013) showed 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 of the size that interests visual inspectors. Hallermann and Morgentahal (2013) have concluded that UAS can be an effective tool for inspecting industrial chimneys and historical buildings. Sa et al. (2015) inspected a high reaching pole with a UAS. 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.

The purpose of this study was to evaluate the use of UAS technology for inspecting bridges. To accomplish this objective, a literature review was first conducted to identify previous studies on the use of UAS for structural inspection and to determine how other transportation agencies in the United States have begun using UAS for engineering-related works. Bridge inspection manuals were also studied in order to identify the parts of an inspection a UAS could potentially satisfy as well as the parts it cannot fulfill. Rules for legal operations were then examined. Afterwards, a small UAS was acquired and used to successfully collect ultra-high-definition video of a large bridge in Independence, Oregon. This report presents the results of this case study, and it then identifies future research and development needs on the use of UAS for bridge inspection.

Chapter 2 Literature Review

2.1 Unmanned Aircraft Systems

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). Figure 2.1 illustrates the main components of a UAS, including the unmanned aircraft, payload, data link, navigation system, ground control station, and human operators. Each of these components is discussed in more detail below.

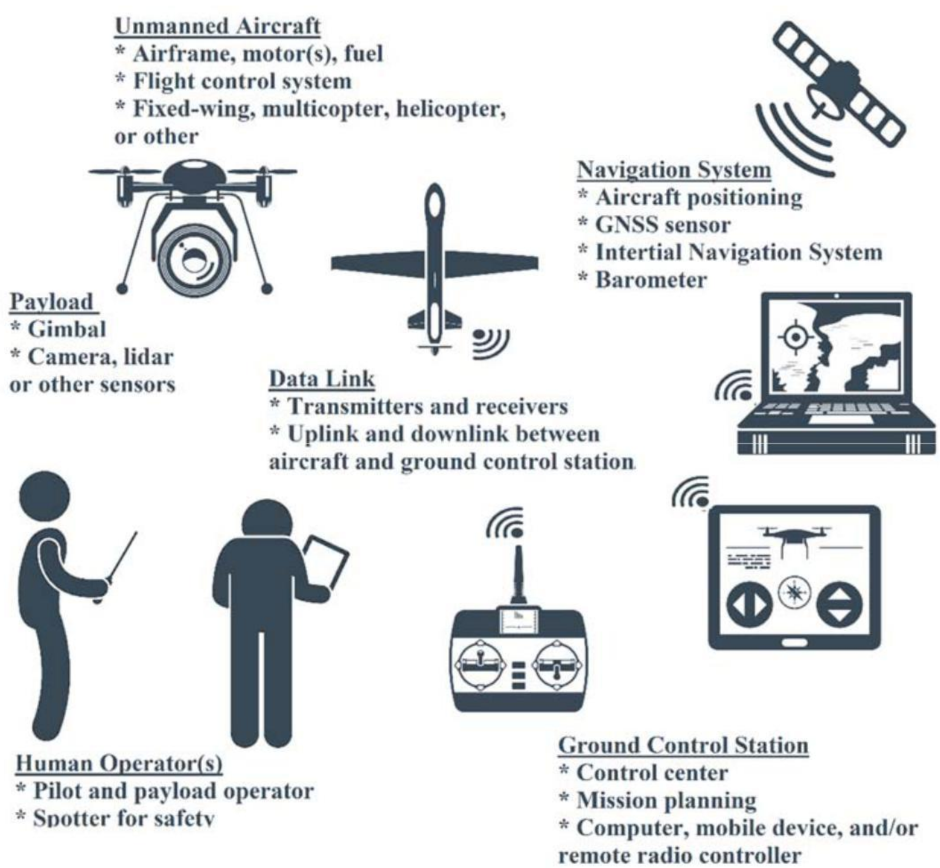

Figure 2.1 Components of an unmanned aircraft system

2.1.1 Unmanned Aircraft

The unmanned aircraft is the flying portion of the system, also commonly referred to as an unmanned aerial vehicle (UAV) or drone. In addition to the airframe, the aircraft includes the motor(s) and fuel, such as batteries or gasoline.

2.1.2 Ground Control Station

The ground control station (GCS) enables the operators to fly the aircraft and control its payload. Generally, the GCS includes at least one radio frequency flight controller with joysticks. For most commercial UAS, the GCS also consists of a computer, tablet, or other mobile device with ground control software wherein a UAS mission can be pre-planned. Such mission plans enable operators to control the aircraft without the use of joysticks. A mission plan consists of a variety of settings that can be specified by the operators, including the flight pattern, flying speed, altitude, and aircraft attitude. The mission plans are pre-loaded into the aircraft prior to takeoff. After takeoff, the operators use the GCS to monitor the status of the aircraft on a digital map and obtain critical information, such as the aircraft's position, altitude, attitude, speed, and battery or fuel level. From the GCS, commands can also be issued to the aircraft to return to its launch point or land. These commands are called "fail-safe" features.

2.1.3 Human Operators

UAS operators are tasked with planning flight missions and issuing the commands to the aircraft. The FAA requires a Pilot in Command (PIC) and also allows a visual observer (also known as a spotter). The PIC has the final say in the operation of the aircraft and is responsible for its navigation and position. Often, the pilot has a video downlink device (e.g., video receiver and monitor) so that he or she can have first-person view from a camera onboard the aircraft. The pilot generally holds a radio frequency flight controller that is capable of pausing or overriding the pre-loaded mission plans, positioning the aircraft with joystick(s), and sending other commands such as to make the aircraft land or return to its launch point. The observer's main responsibility is to maintain continuous vision of the aircraft and to warn the pilot if the aircraft is not in a safe location or not operating properly. Although not required, another person may be necessary for operating the payload sensor.

On August 29, 2016, the FAA approved new rules for non-hobbyist operation of small UAS (14 CFR part 107) (FAA 2016). These new rules allow commercial operations of small UAS (sUAS) which are defined by the FAA as aircraft that weigh less than 55 lbs. Many engineering, surveying, and inspection companies are now complying with "Part 107" rules for legal, commercial UAS operations. According to the Part 107 rules, a pilot in command must do the following:

- Either hold a remote pilot airmen certificate with a small UAS rating or be under the direct supervision of a person who does hold a remote pilot certificate
- Make available to the FAA, upon request, the small UAS for inspection or testing and any associated documents/records required to be kept under the rule
- Report to the FAA within 10 days of any operation that results in at least serious injury, loss of consciousness, or property damage of at least $500
- Conduct a preflight inspection of the sUAS
- Ensure that the sUAS complies with existing FAA registration requirements.

To qualify for a remote pilot airmen certificate, Part 107 requires that a person must

- Demonstrate aeronautical knowledge either by: (1) passing an initial aeronautical test at an FAA-approved knowledge testing center; or (2) holding a Part 61 pilot certificate other than a student pilot, complete a flight review within the previous 24 months, and complete a small UAS online training course provided by the FAA
- Be vetted by the Transportation Security Administration
- Obtain a remote pilot certificate with a small UAS rating
- Be at least 16 years old.

2.1.4 Navigation System

The navigation system is a combination of sensors mounted on the aircraft that allows the operators to monitor the aircraft’s position, velocity, and attitude at all times. The aircraft uses its navigation system when flying a pre-programmed mission or when commanded to land or return to its takeoff position as a fail-safe safety feature during an unexpected emergency. The data from the navigation system are also recorded and stored for analysis after a flight, and they may be used for post-processing other data collected from a payload sensor. The navigation system may comprise one or more Global Navigation Satellite Systems (GNSS) receivers (such as GPS), inertial sensors (gyroscopes and accelerometers, typically mounted in orthogonal triads), barometers, and magnetometers.

2.1.5 Data Link

The data link is the transmission system that enables uplink and downlink between the GCS and the operator. The operator uses an uplink to transmit the mission plans to the aircraft prior to takeoff. These mission plans are then stored in the flight control system of the aircraft. The uplink is also used to communicate real-time flight control commands to the aircraft when needed and to send commands to the payload sensor. The aircraft returns status information on the performance of the aircraft's system (e.g., fuel level, engine temperature), its positioning data, and sometimes imaging data from the payload sensor back to the operator using the downlink.

2.1.6 Payload Sensors

A payload is any equipment transported by the unmanned aircraft. Inspectors will typically desire remote sensing technology on the aircraft, such as video, RGB, thermal, near infrared, and/or multispectral cameras. Lightweight video and RGB cameras are commonly used today; however, some UAS can carry heavier payloads, such as lidar sensors. Often, the payload sensors are attached to the airframe on two or three-axis gimbals to reduce vibrations and motion blur, as well as enable the operator to point the sensor at an object of interest using the GCS and data link.

2.2 Operational Limitations of UAS

In order to maintain the safety of the National Airspace and to ensure that UAS do not pose a threat to national security, the FAA regulates the use of UAS in the United States. The FAA regulates public (i.e., governmental) operations of UAS differently than civil (i.e., non-governmental) operations, but these regulations change frequently, and it is important to be versed in the latest information provided by the FAA. For public operations, the FAA issues a Certificate of Waiver or Authorization (COA) that permits public agencies and organizations to operate particular aircraft for a specific purpose and in a particular area. Since 2012, the FAA has also provided a mechanism for civil operations under Section 333 of Public Law 112-95 (GPO 2012), commonly referred to as rules under a "Section 333 exemption."

As mentioned previously, since August 2016, the FAA has also recently initiated new rules for non-hobbyist operations of small UAS (14 CFR part 107) (FAA 2016). The operational limits under Part 107 are summarized in this report because they are becoming a popular, alternative mechanism for legal, commercial operations of UAS, and it is our intention to provide the latest information. It is worth noting that many of the Part 107 rules are the same as rules specified in a COA or via a Section 333 exemption.

- Some of the noteworthy operational limitations under Part 107 are the following:
- The unmanned aircraft, including its attached systems, payload, and cargo must weigh less than 55 lbs (25 kg) in total.
- The aircraft must remain in visual-line-of-sight of the pilot in command and the person manipulating the flight controls, or a visual observer of the sUAS. The aircraft must be close enough that the operators do not require vision-aided devices other than corrective lenses.
- Small UAS may not operate directly over any persons not participating in the operation who are not under a covered structure or inside a covered, stationary vehicle.
- Operations are limited to daylight or civil twilight (i.e., 30 minutes before or after official sunrise and sunset, respectively).
- The unmanned aircraft must yield the right-of-way to other aircraft.
- A visual observer or spotter is allowed but not required.
- Either the pilot in command or the spotter must maintain continuous visual line-of-sight with the aircraft. A first-person view camera does not satisfy this requirement. (Hence, an observer is often required if the pilot desires use of a first-person view camera.)

- The maximum flying altitude is 400 feet above ground level or within 400 feet of a structure.
- Operations are allowed in Class G (i.e., unregulated) airspace without Air Traffic Control (ATC) permission or in Class B, C, D, and E airspace with ATC permission.
- Weather visibility must be at least 3 miles from the ground control station.
- No person may serve as the pilot in command or observer for more than one unmanned aircraft at a time.
- No operations are allowed from a moving vehicle, in a careless or reckless manner, or while carrying hazardous materials.
- An external load is allowed if the object being carried by the aircraft is securely attached and does not affect the flight characteristics or controllability of the aircraft.
- Most of the above rules are waivable if the applicant demonstrates his or her operation can safely be conducted under the terms of a certificate of waiver.

2.3 Types of Unmanned Aircrafts

An unmanned aircraft is defined as any vehicle that flies without a human onboard. Considering this broad definition, there is an extremely wide range of unmanned aircraft in operation today. They vary significantly 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). Table 2.1 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. Figure 2.2 shows examples of available, professional-grade unmanned aircraft for each subclass.

Table 2.1 Advantages and examples of sUAS

Sub-Class	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
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—especially if using gasoline powered engines	-Alpha Unmanned Systems Sniper; -Swiss UAV KOAX X-240 MK II

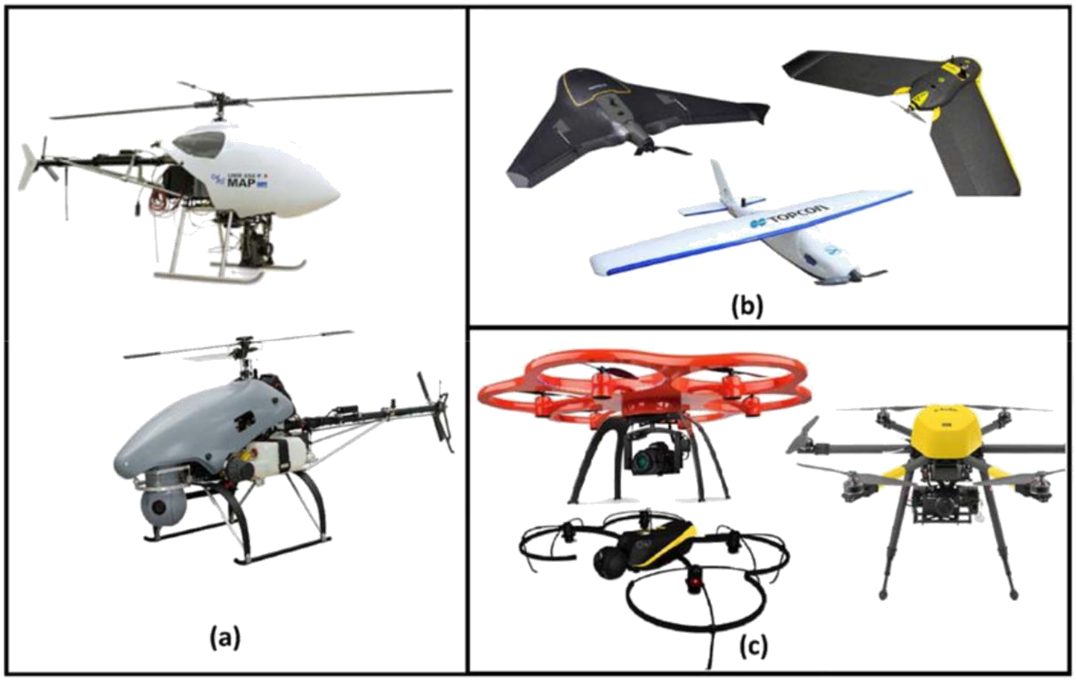

Figure 2.2 Examples of sUAS: (a) helicopters, (b) fixed-wing gliders, and (c) multicopters

2.4 UAS Bridge Inspection

UAS technology appears well suited for bridge inspections. Given the potential safety 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. Several departments of transportation (DOTs) have also conducted feasibility studies on inspecting bridges and other structures with UAS. These studies, along with other DOT studies involving UAS, are summarized in the following section.

2.5 Departments of Transportation Using UAS

The promise of the technology has spurred many DOTs to investigate the potential of applying UAS to solve construction and engineering problems. The majority of topics that are being investigated by the DOTs can be classified into four main groups: traffic monitoring, structural inspection, construction site inspection, and other applications. Table 2.1 shows which state DOT has been researching each of these topics. A brief summary of UAS operations for each state is also given below.

Table 2.2 Example usage of UAS in various departments of transportation

DOT	Traffic Monitoring	Structural Inspection	Construction Site Inspection	Other Applications
Arkansas	X			
California				X
Connecticut		X		
Florida		X		
Georgia	X			
Michigan	X	X		X
Minnesota		X		
North Carolina				X
Ohio		X		X
Texas				X
Utah			X	
Washington	X			X
West Virginia	X		X	

2.5.1 Arkansas DOT

Arkansas DOT researchers have evaluated tools that could be used to model real-time traffic movements. Early on, UAS were a part of the evaluation. However, the researchers later concluded that while UAS has the potential to be an effective tool for collecting traffic data, “with FAA restrictions and the time schedule for this particular project, UAVs were not applicable for AHTD at this time” (Frierson, 2013).

2.5.2 CalTrans

Researchers at CALTRANS are exploring the possibility of using UAS for evaluating the stability of slopes. They have researched what other institutions and agencies are working on and whether others are exploring this potential application of UAS (CTC, 2014).

2.5.3 Connecticut DOT

Connecticut DOT has recently begun investigating the use of new technologies for bridge inspections. They have identified UAS as a potential candidate for improving the state of inspections. They released a press release (ConnDOT, 2015) that explains their intention to do a UAS demonstration inspection on December 16, 2015.

2.5.4 Florida DOT

Otero et al. (2015) have identified UAS as a potential tool to aid bridge inspectors. They were able to perform many tests indoors to evaluate the technology in hazardous flying situations. The researchers’ findings gave them confidence to perform 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. Two field tests were done at the Florida Tech main campus, and three were performed at FDOT selected sites. 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 and analysis of the imagery collected, such as a detailed cost estimation including total inspection time.

Along with testing a UAS to collect imagery useful to a bridge inspector, the research group has also begun preliminary tests to determine 1) the amount of necessary time for training UAS pilots, and 2) cost estimates and cost savings of using UAS instead of other traditional equipment. They state that more testing is needed before they can provide detailed conclusions.

2.5.5 Georgia DOT

To explore the feasibility of using UAS in Georgia DOT operations, Irizarry and Johnson (2014) conducted interviews with staff in four Georgia DOT divisions. Based on vehicle, control station, and type, the results of those interviews led to the proposal of five tools that involve UAS. The five proposed tools were named flying camera, flying total station, perching camera, medium altitude long endurance, and complex manipulation. All of the tools are intended to facilitate transportation monitoring, and this research is ongoing.

2.5.6 Michigan DOT

Brooks et al. (2015) have been investigating several applications of UAS technology. These researchers have been using UAS for traffic monitoring as well as for three - dimensional reconstruction of sites. Their project tested and evaluated five main platforms with a combination of optical, thermal, and lidar sensors to assess critical transportation infrastructure and issues, such as bridges, confined spaces, traffic flow, and roadway assets. They concluded that UAS can help with many transportation issues, including traffic monitoring and bridge element inspection.

2.5.7 Minnesota DOT

Collins Engineers studied the effectiveness of utilizing UAS technology for bridge safety inspections (Lovelace, 2015). The group studied four bridges located in Minnesota. Collins

Engineering contracted Unmanned Experts to use an Aeyron Skyranger multicopter with several imaging devices to collect different types of data, including still images, videos, and infrared. The research group made a great number of conclusions after the completion of the four inspections. They concluded that UAS are a suitable tool to perform the following:

(1) Safe inspections of large bridges as they have more space to maneuver; however, they noted that there are situations that a UAS can be used to enhance the inspection of small bridges (i.e., culvert intake inspection, banks upstream and downstream);

(2) Pre-inspection surveys of the banks of the rivers, clearance heights, and locations of anchor points for climbing gear.

Lovelace (2015) also concluded that close-up photos can be obtained that are useful in visual inspection with a UAS. However, the UAS used in their study was heavily dependent on GNSS positioning, and future studies would be enhanced if a UAS designed specifically for inspections was used. Lovelace (2015) also noted that tactile functions (e.g., cleaning, sounding, measuring, and testing) cannot be replicated using a UAS, and that safety risks associated with traffic control, such as working at height and in traffic, could be minimized with the use of UAS technology.

2.5.8 North Carolina DOT

North Carolina is lobbying for support to develop a UAS program. Estes (2014) described UAS missions performed at the North Carolina UAS test site. The study demonstrated the results of flights done at the Hyde County test sites and gives estimated economic impacts on the county and state if UAS were implemented.

2.5.9 Ohio DOT

Ohio DOT has used a UAS to capture aerial imagery and develop digital surface models. Judson (2013) described the UAS platform in detail, the data collected, and how results were used. The agency noted that the biggest challenge associated with the use of a UAS is not the flying but the work required to prepare to fly (i.e., meeting FAA regulations and coordinating with local air traffic control).

2.5.10 Texas DOT

Hart and Gharaibeh (2011) investigated the feasibility of using sUAS to assess its effectiveness and safety in performing roadside condition and inventory surveys. Their study involved performing roadside condition surveys in three locations, both traditionally and with a sUAS, along highways of varying usage. The conditions of the sites were assessed twice on the ground to produce “ground truth,” and then this was compared to the results from the UAS imagery and video. The study showed that the majority of the observations with the UAS matched with observations made on the ground.

2.5.11 Utah DOT

Barfuss (2012) examined the use of high-resolution aerial photography obtained from a UAS to aid in monitoring and documenting state roadway structures and associated issues. Using georeferenced, UAS-obtained high-resolution aerial photographic imagery, the project documented the before, during, and after stages of the Southern Parkway construction near the new Saint George International airport. Researchers also photographed and classified wetland plant species.

2.5.12 Washington State DOT

In support of the Washington State DOT, McCormack (2008) evaluated the use of a UAS as an avalanche control tool on mountain slopes above state highways. The unpopulated flight areas made UAS an ideal tool for monitoring avalanches and supplementing routine avalanche operations. The UAS monitoring the avalanches also captured aerial images that were deemed adequate for traffic surveillance.

2.5.13 West Virginia DOT

Gu (2009) demonstrated the feasibility of monitoring traffic congestion, work zone management, and safety with a remotely controlled aircraft. They used a UAS in this project equipped with a GPS receiver, a flight data recorder, downlink telemetry hardware, a digital still camera, and a shutter triggering device to conduct a proof-of-concept demonstration of aerial data acquisition. Gu (2009) concluded that UAS is a low-cost means to acquire high resolution, geotagged images.

2.6 Bridge Inspection Manuals

To determine the extent to which a UAS can effectively perform a bridge inspection, bridge inspection manuals were reviewed. AASHTO's Manual for Bridge Evaluation states that there a several types of bridge inspections (AASHTO, 2011). They are as follows:

- Initial Inspections – inspection (primarily done visually) that sets the baseline for all future inspections.
- Routine Inspections – regularly scheduled inspections that are done to determine whether additional inspections are needed.

- Damage Inspections – inspections that are scheduled after damage is found during a routine inspection.
- In-depth Inspections – in-depth inspections are scheduled inspections that include "hands on" scraping, cleaning, and probing.
- Fracture-critical Inspections – inspections tailored to bridges that are identified as fracture-critical. This designation is given to bridges that would partially or entirely collapse in a rapid manner should a steel member fail in tension.
- Under-water Inspections – inspection done when critical elements reside beneath the surface of the water.
- Routine Wading Inspections – regularly scheduled inspections of piers and abutments that are only accessible by wading.
- Special Inspections – inspections designed for special case bridges. These are identified during routine inspections.

All of these different types of inspections can be divided into two groups: visual and physical. Initial and routine inspections are primarily done visually; they are performed in order to determine whether an In-depth Inspection with a more "hands-on" approach is needed. The current state of the technology will limit UAS primarily to visual inspections. Any probing, coring, scraping, or cleaning as described in AASHTO (2011) is not currently possible with a typical UAS.

The FHWA requires that every bridge inspection is accompanied by a bridge inspection report. The reports are required to contain information on what they classify "Inventory Items, Condition Ratings, and Appraisal Items." The following is taken directly from FHWA's Bridge Inspector's Reference Manual (Ryan, 2008) on the necessary items of a report:

“Inventory items pertain to a bridge’s characteristics. For the most part, these items are permanent characteristics, which only change when the bridge is altered in some way, such as reconstruction or load restriction. Inventory Items [include the following]:

- Identification – Identifies the structure using location codes and descriptions.
- Structure Type and Material – Categorizes the structure based on the material, design and construction, the number of spans, and wearing surface.
- Age and Service – Information showing when the structure was constructed or reconstructed, features the structure carries and crosses, and traffic information.
- Geometric Data – Includes pertinent structural dimensions.
- Navigation Data – Identifies the existence of navigation control, pier protection, and waterway clearance measurements.
- Classification – Classification of the structure and the facility carried by the structure are identified.
- Load Rating and Posting – Identifies the load capacity of the bridge and the current posting status. This item is subject to change as conditions change and is therefore not viewed as a "permanent" item.
- Proposed Improvements – Items for work proposed and estimated costs for all bridges eligible for funding from the Highway Bridge Program.
- Inspection – Includes latest inspection dates, designated frequency, and critical features requiring special inspections or special emphasis during inspection.”

“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. Condition rating items include:

- Deck – Describes the overall condition rating of the deck. This condition of the surface/protective systems, joints, expansion devices, curbs, sidewalks, parapets, fascia, bridge rail and scuppers is not included in the rating, but the condition will be noted in the inspection form. Decks that are integral with the superstructure will be rated as a deck only and not influence the superstructure rating.
- Superstructure – Describes the physical condition of all the structural members. The condition of the bearings, joints, paint system, etc. will not be included in the rating except for extreme situations, but the condition will be noted in the inspection form.
- Superstructures that are integral with the deck will be rated as a superstructure only and not influence the deck rating.
- Substructure – Describes the physical condition of piers, abutments, piles, fenders, footings or other components.
- Channel and channel protection – Describes the physical condition that is associated with the flow of the water through the bridge which include the stream stability and the condition of the hydraulic countermeasures.
- Culvert – Evaluates the alignment, settlement, joints, structural condition, scour and any other of the items that may be associated with a culvert."

"Condition ratings are a judgment of a bridge component condition in comparison to current standards.

"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:

- Structural Evaluation – Overall evaluation of the structure based on the lowest bridge component condition rating, excluding the deck, superstructure, substructure, channel and channel protection and culverts. This item is calculated by the FHWA Edit/Update program.
- Deck Geometry – Evaluates the curb-to-curb bridge roadway width and the minimum vertical clearance over the bridge roadway. This item is calculated by the FHWA Edit/Update program.
- Under-clearances, Vertical and Horizontal – The vertical and horizontal under-clearances from the through roadway under the structure to the superstructure or substructure units. This item is calculated by the FHWA Edit/Update program.
- Waterway Adequacy – Appraises waterway opening with respect to passage of flow under the bridge.
- Approach Roadway Alignment – Comparing the alignment of the bridge approaches to the general highway alignment of the section of highway that the structure is on.
- Traffic Safety Features – Record information on bridge railings, transitions, approach guiderail, approach guiderail ends, so that evaluation of their adequacy can be made.
- Scour Critical Bridges – Identify the current status of the bridge regarding its vulnerability to scour."

UAS has the potential to aid in inspecting a number of the items discussed above. Tables 2.2 to 2.5 summarize how a UAS can or cannot satisfy the required items.

Table 2.3: Bridge Report inventory items that UAS can facilitate

REPORT REQUIREMENT	AIDED BY UAS? (Y/N)	HOW IT CAN BE AIDED OR WHY IT CANNOT
Identification	N	This information will be known prior to any field inspection with a UAS.
Structure Type and Material	Y	High Resolution photos of the structure can display the type and the material of the bridge.
Age and Service	Y	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	Y	Previous records of geometric values can be compared with geometries acquired from 3D reconstructions of the imagery collected during a UAS inspection
Navigation Data	Y	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	N	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	N	This would be better performed by the engineer on the ground. Signage is easily accessible from the ground.
Proposed Improvements	N	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 accessing the bridge.
Inspections	N	This section refers to previous inspections performed. This data would be recorded previously.

Table 2.4: Bridge Report condition ratings that UAS can facilitate

REPORT REQUIREMENT	AIDED BY UAS? (Y/N)	HOW IT CAN BE AIDED OR WHY IT CANNOT
Deck	Y	Geometry of Deck as well as presence of defects could be identified via high resolution imagery
Superstructure	Y	Presence of cracks and other defects can be identified as well as monitored though imagery collected from regular UAS flights over time
Substructure	Y	Presence of cracks and other defects can be identified as well as monitored though imagery collected from regular UAS flights
Channel and Channel Protection	Y	Hydraulic countermeasures could be visually monitored by regular inspection by a UAS. The bank conditions can be monitored through low altitude flights.
Culvert	Y	Any exterior blockage of culverts that are not entirely submerged can be identified by a UAS

Table 2.5: Bridge Report appraisal items that UAS can facilitate

REPORT REQUIREMENT	AIDED BY UAS? (Y/N)	HOW IT CAN BE AIDED OR WHY IT CANNOT
Structural Evaluation	Y	Presence of cracks and other defects can be visually identified as well as monitored though imagery collected from regular UAS flights
Deck Geometry	Y	The geometry of the deck can be recorded in imagery with proper ground control
Under-Clearances	Y	Clearance values and opening can be potentially measured by 3D reconstructions of the UAS imagery
Waterway Adequacy	Y	Waterway openings can be recording and captured with high resolution photography from a UAS
Approach Roadway Alignment	Y	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	Y	A UAS can provide views of the outer side of bridge railings
Scour Critical Bridges	Y/N	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

Chapter 3 Experimentation

To begin evaluating the use of UAS for inspecting bridges, a small quadcopter was flown along a large bridge in western Oregon. The objective of the flights was to investigate its capability of acquiring imagery that a bridge inspector could use to supplement an inspection. Imagery of the following items on the bridge were collected for the following purposes:

- Connections – investigate the condition of bolts, rivets, possible pack rust, etc.
- Bearings – evaluate alignment, possible movement, bulging or tearing, etc.
- Joints – look for leakage, concrete spalling, steel section loss, cracking, etc.
- Banks – view conditions upstream and downstream of the bridge, search for erosion, scour
- Other structural members in locations that are difficult to physically access

3.1 Bridge Site for Test Inspection

The UAS flights were conducted along the Independence Bridge, a deck-plate girder bridge over the Willamette River on River Road South, Marion County, Oregon (see Figure 3.1). The Independence Bridge is rated as a "large bridge" and is under the responsibility of the Marion County, Oregon, Bridge Inspection program. It was originally constructed in 1951 and rehabilitated in 1985. It has a total length of 675.4 m, longest span of 46.3 m, total deck width of 7.9 m, and total deck area of 2,787 square meters. Although the deck, superstructure, and substructure appear to be in good condition, the bridge is fracture critical (i.e., failure of a steel member would cause a portion of or the entire bridge to collapse).

Figure 3.1 Independence Bridge over the Willamette River, Oregon

3.2 Unmanned Aircraft System for Test Inspection

A DJI Phantom 3 Pro multicopter equipped with a gimballed camera capable of collecting ultra-high-definition 4k video and 12 megapixel photography was selected for the tests (figure 3.2). Multicopters are ideal for inspections because they are easy to maneuver, can hover in place, allowing the operator to point the camera at features of interest, and are capable of vertical take-offs and landings. The Phantom was chosen simply because it was the only multicopter available to the project team and authorized by a COA from the FAA for this experiment. The Phantom is also a popular system for hobbyists and some engineering companies. However, the team recognizes that numerous other systems are available on the market, and some may be better suited for performing structural inspections.

Figure 3.2 DJI Phantom 3 Pro, Pilot, and controller

3.3 Mission Operations

Several UAS flights were conducted on September 21, 2015. During each flight, the pilot used first-person view technology for positioning the aircraft within 3 to 5 meters of the bridge girders, and a visual observer maintained line-of-sight with the aircraft. First-person view video was broadcast in real time to an Apple iPad Mini tablet mounted on top of the radio frequency flight controller (figure 3.2). While hovering close to the girders, the pilot rotated the pitch up and down on the gimballed camera and captured the 4k video. The aircraft was then slowly flown parallel to the girder to the next hovering point, and additional video was captured in the same manner. The first-person view camera was helpful for navigating the aircraft while ensuring that video was acquired of desired features of the bridge. In addition, a bridge inspector looked at the video feed in real time and occasionally asked the pilot to adjust position in order to capture more imagery of interesting parts on the bridge. Every 15 minutes, the Phantom was landed and batteries were swapped.

Chapter 4 Results and Discussion

The UAS successfully collected 55 minutes of ultra-high-definition video of both the upstream and downstream sides of the bridge superstructure and substructure. This video is available from the first author upon request. Although the video is more useful for evaluating the utility of the UAS for inspecting the bridge, some still imagery was extracted from the video (figures 4.1 to 4.7) in order to present some examples of the results in this report. These images show some of the capabilities of UAS technology for evaluating the conditions of bearings, connections, and joints on the bridge. Some discussion of the results of this experiment are also given in Gillins et al. (2016). Figure 4.1 shows a bearing and joint on the bridge with some leakage. The image shows that tar from a previous repair on the deck had leaked and pooled on top of the concrete support tower. Figure 4.2 presents some of the bolts and bolt patterns at the joints of steel members that could be analyzed for possible rust. Some cracking of a concrete guard rail is evident in figure 4.3. Figure 4.4 depicts an important connection between two of the steel girders on the bridge. Figure 4.5 shows the bearing of a steel beam on a concrete tower, and it appears that a nut is missing on one of the bolts in the connection. Efflorescence was evident on many of the concrete towers directly beneath the steel beams (e.g., figure 4.6).

In addition to collecting video of the bridge, the aircraft was also flew along the banks of the river on both the upstream and downstream sides of the bridge. Flying and capturing video of the banks was quite simple (especially when compared to flying in close proximity to the bridge), and it enabled the inspector to quickly assess and document any possible erosion issues near the bridge. During the flights of the banks of the river, the aircraft was flown at a speed of approximately 1-3 meters per second. This speed was chosen because it simulates the approximate speed at which a human could walk the banks and look for potential problems.

Figure 4.1 Evidence of a leaking joint

Figure 4.2 Example imagery of bolt patterns at steel connections

Figure 4.3 Cracking of a concrete railing

Figure 4.4 Connection of a steel member to a concrete tower; note the missing bolt nut

Figure 4.5. Connection of two steel girders

Figure 4.6 Efflorescence on concrete columns

Figure 4.7 Bank of the river upstream of the bridge

Although beneficial video was captured of the bridge and the surrounding area, the team noticed several challenges worth future research and development. The following discusses some of the identified challenges and recommends some strategies for alleviating them.

4.1 Resolution

Bridge inspectors need very high-resolution imagery in order to evaluate the condition of many of the small details on the bridge, such as each of the bolts and nuts at each joint. The need for high resolution imagery is further compounded during an in-depth inspection, at which the Bridge Inspector’s Reference Manual requires the inspector to view elements of the bridge at an “arm’s length” standoff distance (Ryan 2008). As a brief discussion of this challenge, in bright light Blackwell (1946) estimated the resolution of the human eye as 0.7 arc-minutes. For an average human, arm’s length is approximately 63.5 cm. For small angles, the following simple relationship enables estimation of spatial resolution as a function of angular resolution:

$$S \quad R \tag{4.1}$$

where S = the distance subtended at a standoff distance R by an arc of θ in radians. Setting R = 635 mm and θ = 0.7 arc-minutes, the spatial resolution of a human eye at arm's length is estimated as only 0.1 mm.

Acquiring imagery with this level of spatial resolution is quite difficult with the consumer-grade cameras that are typically mounted on a UAS. For example, the resolution of the ultra-high-definition video recorded by the camera mounted on the Phantom 3 Pro is up to 4096 x 2160 pixels. Its camera sensor has a width of 6.17 mm and a focal length of 3.6 mm. The spatial resolution can be estimated by these camera parameters by the following relationship:

$$S \quad \frac{SW\,R}{f\;\;PW} \tag{4.2}$$

where SW = sensor width, R = standoff distance, f = the focal length, and PW = the width of the image in pixels.

During the flights, the closest standoff distance of the aircraft from the bridge was roughly 3 meters. Setting R = 3000 mm in Eqn. 4.2 and PW = 4096 pixels, the spatial resolution (S) is estimated to equal 0.73 mm. This resolution is much coarser than the resolution of the human eye at arm's distance.

Of course, flying closer to the structure increases the likelihood of a crash. One possible solution is to use a camera with a larger sensor focal length and/or a camera equipped with an optical zoom. A zoom feature may enable collection of higher-resolution imagery without the need to fly so close to the structure.

4.2 Obstructions

Because of the need to collect high resolution imagery as discussed above, operators must fly the UAS very close to the structure. However, at short standoff distances, the structure may obstruct or degrade satellite signals. If observers are attempting to fly underneath a structure (e.g., beneath a bridge deck), the satellite signal may be completely blocked. GNSS sensors are commonly installed on a UAS for assisting the operator during flight. When flying a multicopter, GNSS enables the aircraft to hover in place. GNSS is also used to navigate the aircraft during pre-programmed Waypoint-Assisted Missions. When a UAS is flown underneath or in close-proximity to the bridge, the satellite signals may not be reliable. Other flight-assistance sensors are needed to reduce the reliance on GNSS for positioning and navigation. Some aircraft are equipped with ultrasonic sensors that can be used to detect obstacles or hold the aircraft at a fixed distance from a structural member.

Inspecting the underside of the bridge deck presents another challenge. For some aircraft, like the Phantom 3 Pro, the camera is mounted beneath the rotors. Thus, the camera cannot be pointed to capture imagery directly above the aircraft. A UAS equipped with a front-mounted camera is more useful for capturing imagery beneath structures.

4.3 Wind

Some of the small UAS are lightweight, and strong wind gusts have the potential to push the aircraft in unexpected directions. The Phantom 3 Pro only weighs 1.28 kg, and a 12 knot wind gust will affect it during flight. This issue is complicated by flying in close proximity to a bridge. Bridges over wide rivers or canyons are commonly in natural "wind tunnels," and complicated wind eddies can form near the bridge. A heavier multicopter is better suited for flying through strong wind gusts.

4.4 Lighting

Digital cameras are passive sensors, and poor lighting degrades the quality of the imagery. During certain times of day, especially near sunrise and sunset, shadows or overly bright spots may be on the bridge. Use of a camera in poor lighting can result in over- or under-exposed imagery that may make it difficult to find defects on the bridge. Typically, flights during midday or in overcast weather are best for optimizing the natural lighting conditions. However, lighting is generally always poor when imagery is captured underneath the bridge deck. Flash lights or head beams could help alleviate this issue. In addition, computer science tools might be used to post-process and enhance the quality of the UAS-derived imagery. Additional tools need to be developed to for accounting for poor lighting conditions. Real-time tools need to be developed for changing the aperture size of the camera during flight.

Chapter 5 Conclusions

UAS has great potential for reducing some of the dangers and costs associated with a bridge inspection. Further, as documented in this report, UAS can be beneficial for a number of additional transportation engineering-related problems, such as for monitoring traffic, inspecting construction sites, surveying and mapping, performing roadside condition inventorying, etc. In this study, a small quadcopter was flown to collect ultra-high-definition video of a large bridge in Independence, Oregon. A number of minor bridge defects could be noted in the imagery, including rust, missing nuts, efflorescence, cracks, and spalling. The videos could be used to satisfy many of the routine and initial bridge inspection requirements of the AASHTO Bridge Inspection Manual (AASHTO, 2011). The imagery may also be useful for in-depth inspections; however, in-depth inspections sometimes require probing and scraping that cannot be accomplished with UAS. In addition, in-depth inspections require the inspector to be at arm's length of the bridge. Obviously, a UAS does not satisfy this requirement, but imagery collected from a UAS can be of high resolution.

A few challenges were noted in this report. Perhaps the greatest challenge involves capturing imagery with a UAS with sufficient resolution for an inspection. At arm's length, the human eye has a spatial resolution approximately equal to 0.1 mm. Even within 3 meters of the bridge, the approximate spatial resolution of the high-definition camera onboard the quadcopter in this experiment was 0.7 mm. Flying even closer to the bridge is difficult because of complicated wind eddies that can potentially push the aircraft into the structure. However, this problem could be alleviated by flying a heavier aircraft equipped with a camera with a larger sensor size and an optical zoom. Future research remains to investigate other UAS platforms for bridge inspection.

It is worth noting that the authors have been awarded a two-year grant from the Oregon Department of Transportation (ODOT) to conduct additional field tests. In this grant, the team will fly additional bridges using other sizes of multicopters and cameras. In addition, the team will acquire imagery during official bridge inspection(s) conducted by ODOT. The costs and benefits of these tests will be documented in a future ODOT research report.

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