EYES IN THE SKY: BRIDGE INSPECTIONS WITH UNMANNED AERIAL VEHICLES

Final Report

SPR 787

Oregon Department of Transportation

EYES IN THE SKY: BRIDGE INSPECTIONS WITH UNMANNED AERIAL VEHICLES

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Abstract Interest in the use of unmanned aircraft systems (UAS) in bridge inspection is rapidly growing within State transportation agencies, due to potential cost and time savings, as well as safety benefits. In particular, UAS may provide the capability to reduce use of bucket trucks, climbing, and lane closures in some inspections, by enabling high-resolution video and still imagery of bridge elements to be acquired from multiple viewing angles using onboard cameras. Additionally, imagery acquired with the UAS can be post-processed and further analyzed back in the office, facilitating detailed analysis and a possible shift of some tasks from the field to the office. However, in evaluating the use of UAS in bridge inspection, it is critical to understand both the capabilities and limitations of UAS, the aspects of an inspection that UAS can and cannot be used to satisfy, the regulatory aspects of UAS use, and the recommended operational procedures and workflows. Additionally, to assist ODOT and other transportation agencies in deciding whether to implement UAS-based inspection programs and procedures, cost-benefit information is needed. This research project focused on addressing these needs. Because required inspections of communication towers pose similar safety and logistical concerns, this project also investigated the potential use of UAS in ODOT's tower inspection program. Following a literature review and a detailed analysis of UAS components and advantageous characteristic for structural inspections, six bridge inspections and three tower inspections were conducted. The results were used to compile recommended safety and operational procedures and to assess, item-by-item, the required reporting elements of an FHWA inspection report that can or cannot be aided by use of UAS. Finally, the project findings were used in conjunction with data provided by ODOT to perform a cost-benefit analysis for use of UAS in bridge inspection. The analysis yielded an estimated average cost savings of approximately $10,000 per bridge inspection and showed a benefit-cost ratio of 9 if a UAS bridge inspection program is implemented.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
	NOTE: Volumes greater than 1000 L shall be shown in m^3.			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
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m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

DEDICATION

In loving memory of Thomas N. Gillins (1957 ~ 2015), regional and national bridge engineer for the US Forest Service. His ideas spurred pursuit of this research by his sons, Daniel and Matthew.

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DISCLAIMER

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1.0 INTRODUCTION

1.1 OVERVIEW

As the most common method of transporting people and goods across dangerous and difficult terrain, bridges are vital to 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 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 or under-bridge inspection units ("snooper cranes" or bucket trucks) 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, and/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.

Recently, there has been growing interest in the use of unmanned aircraft systems (UAS) for alleviating some of these challenges in bridge inspection. Due to their high 3D maneuverability, small UAS can be used to remotely acquire close-up, highly resolute 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, imagery and other data acquired from a UAS can be post-processed and analyzed at a later time, enabling some of the work associated with an inspection to be shifted from the field to the office. Through the possible reduction in lane closures, use of climbing and under-bridge inspection units and shifting of some analysis from field to office, UAS have the potential to both reduce costs and enhance safety in bridge inspection. Additionally, UAS can be flown frequently at a low cost in order to monitor changes on a structure over time. However, for transportation agencies to determine whether to implement use of UAS in inspections and to develop procedures for their use, information is required on both the capabilities and limitations of UAS, the regulations pertaining to UAS use, and the costs and benefits associated with the procurement and operational use of UAS.

1.2 OBJECTIVES

This project (SPR 787, “Eyes In The Sky: Bridge Inspections With Unmanned Aerial Vehicles”: ODOT Agreement 30530, Work Order 16-05), was conducted with the overarching objective of evaluating and documenting the effectiveness of inspecting bridges with small unmanned aircraft systems (sUAS). The primary goal was to document the capabilities and limitations of performing structural inspections with UAS. Based on this goal, the following key project tasks were identified:

1. Evaluate the performance of UAS-based methods for inspecting bridges and communication towers.

2. Identify which ODOT inspection requirements can and cannot be satisfied with a UAS inspection.

3. Provide a cost-benefit analysis of performing UAS inspections for communication towers and bridges.

4. Develop procedures/guidelines for how to safely and effectively perform UAS inspections of bridges and communication towers.

Although the main focus of this research and report was on inspecting bridges, at the request of ODOT, the team also investigated the utility of UAS for inspecting some wireless communication towers. Similar to bridges, communication towers also need to be routinely inspected, often requiring climbing, bucket trucks, and ropes and harnesses. Because the inspection of bridges and communication towers present similar safety concerns, and because UAS could potentially reduce their inspection dangers and costs, UAS could benefit the inspection of both types of structures. Most of the steps required for inspecting a bridge with a UAS are similar or identical to the corresponding steps for executing a UAS inspection of a wireless communication tower.

1.3 REPORT ORGANIZATION

The remainder of this report is organized as follows: Chapter 2 provides an overview of UAS and their use in transportation engineering, including types and components of UAS, regulations applicable to UAS, use by Departments of Transportation (DOTs), and key findings from the literature review conducted as part of this study. Chapter 3 describes the equipment and methodology followed in this work, including safety planning, regulatory compliance, and operational workflows. Chapter 4 describes the UAS test inspections performed in this study, including six bridge inspections and three communication tower inspections. Numerous examples of imagery acquired from the unmanned aircraft are included. Chapter 5 includes a detailed discussion of the results and important findings from the bridge and tower inspections and subsequent analysis of the imagery. The results of a cost-benefit analysis are also presented in Chapter 5. Finally, the conclusions from the study are presented in Chapter 6.

2.0 BACKGROUND ON UNMANNED AIRCRAFT SYSTEMS AND PRIOR USE IN TRANSPORTATION ENGINEERING

This chapter provides a brief background on the basic components and types of unmanned aircraft systems (UAS). Information is then provided on the U.S. Federal Aviation Administration (FAA) rules for operating a UAS, and the important findings from a literature review on the use of UAS for transportation engineering applications.

2.1 BASIC COMPONENTS OF UAS

The FAA defines a UAS as not only 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" (FAA 2015a). Figure 2.1 illustrates the basic components of a UAS, and the following sections summarize each of these components.

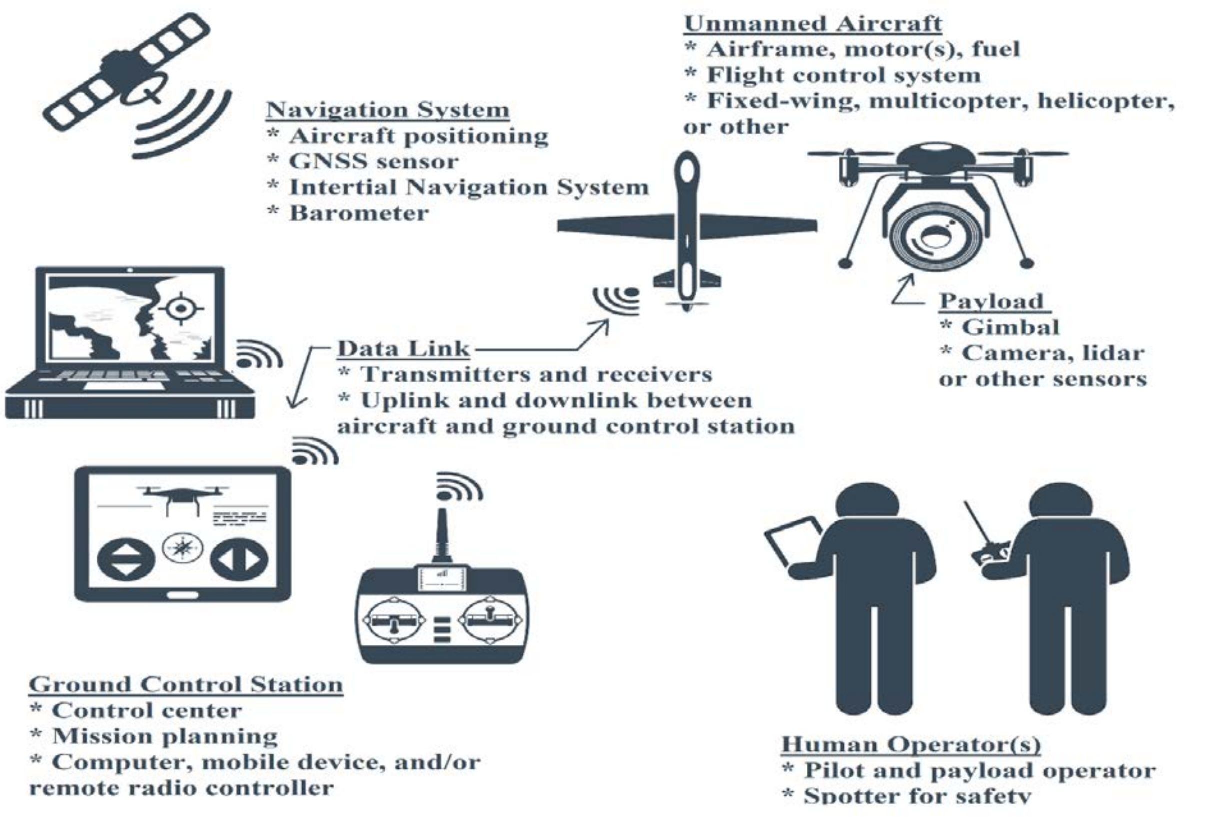


Figure 2.1: Basic Components of an Unmanned Aircraft System

2.1.1 Unmanned Aircraft

Any aircraft that can be flown without a human on board is considered an unmanned aircraft. The FAA 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 2015a). The aircraft includes the motor(s) and fuel, such as batteries or gasoline. Unmanned aircraft are also referred to in the literature as unmanned aerial vehicles (UAVs) or drones. (While widespread differences in terminology exist, this report adheres, wherever possible, to the terms and definitions used by the FAA.)

Within the broad heading of unmanned aircraft, a number of distinct categories or types can be defined, varying 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 or multirotors), helicopters, airships, and balloon systems. Within each of these categories, large variations in size and weight also exist. However, the most common types used in civilian applications fall under the category of small UAS (sUAS). A sUAS is a UAS (including aircraft and all attachments) that weighs less than 55 lb (25 kg). On August 29, 2016, the FAA released a new sUAS rule designed to facilitate integration of sUAS into the National Airspace for commercial use. The new sUAS rule (officially, Title 14 CFR Part 107) (FAA 2016) is summarized later in this chapter of the report and is referred to hereinafter as "Part 107 rules."

Table 2.1 divides the sUAS into three common subclasses: fixed-wing gliders, multicopters, and helicopters. This table summarizes the advantages of each subclass based on a study in Otero et al. (2015) and also gives some examples of professional-grade, turn-key systems on the market. (Note that many systems are currently available and this list is only meant to give some examples. Numerous consumer-grade options also exist for each of these subclasses.)

Table 2.1: Examples of sUAS in Various Sub-Classes and Their Corresponding Advantages

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 (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

2.1.2 Ground Control Station

The Ground Control Station (GCS) is the control center for the operation of the UAS. It enables the operator to fly the aircraft and control its payload. It is also usually the center in which a flight mission can be pre-planned onsite, if necessary. A mission plan consists of a variety of settings that can be specified prior to the flight, including flightlines, flying speed, altitude, and aircraft attitude. Most mission planning software will also enable camera stations (i.e., exposure locations) and image acquisition parameters to be specified, and some software will work backwards from the desired imagery specifications to automatically calculate other mission parameters, such as flight altitude and flightline spacing. For many systems, the mission plans are pre-loaded into the aircraft prior to takeoff. After takeoff, the operator uses the GCS to monitor the status of the aircraft and obtain critical information, such as the aircraft's position (for some systems, on a digital map), altitude, attitude, speed, and battery or fuel level. From the GCS, commands can also be issued to the aircraft to pause its flight, over-ride or change the flight mission, or request the aircraft to return to its launch point or even land if a problem arises. For many systems, a radio frequency flight controller is available for piloting the aircraft with joysticks. For most commercial UAS, the GCS also consists of a laptop, tablet, or other mobile device with ground control software.

2.1.3 Human Operators

Human operators are tasked with planning flight missions and issuing the commands to the unmanned aircraft. All operations require a remote pilot in command (PIC), and some also require one or more visual observers. The person operating the controls may be the remote PIC, or another crew member under the direct supervision of the remote PIC. The controls typically comprise a radio frequency flight controller that is capable of pausing or overriding the pre-loaded mission plans, positioning the aircraft, and sending other commands such as to make the aircraft land or return to its launch point. For safer operations, the flight crew may make use of a video downlink device from a camera onboard the aircraft to enable a "first-person view" of obstacles. The first-person view provides a similar perspective as if the operator were actually onboard the aircraft during flight. However, it is important to note that first-person view cannot be used to satisfy FAA "see and avoid" requirements. The pilot and/or other crewmembers monitor the GCS and often operate a payload sensor. A visual 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. For some operations, another person may be necessary for assisting with the operation of the payload sensor (e.g., triggering and/or pointing a camera on the payload while a pilot flies the aircraft).

2.1.4 Navigation System

The navigation system comprises a combination of sensors mounted on the aircraft that allow the operator(s) to monitor the aircraft's position, altitude, velocity, and attitude at all times. The aircraft uses its navigation system when flying a pre-programmed mission and when commanded to land or return to its takeoff position as a safety feature during an unexpected emergency. The data from the navigation system is also recorded and stored for analysis after a flight, and it may be used for post-processing other data collected from a payload sensor. The navigation system may comprise one or more GPS receivers, 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 aircraft. The operator uses an uplink to transmit real-time flight control commands to the aircraft 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. Geospatial professionals will typically install remote sensing technology on the aircraft, such as video, red-green-blue (RGB), thermal infrared, near infrared, and/or multispectral cameras. Lightweight video and RGB cameras are commonly used today; however, some UAS can carry heavier payloads, including small 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 enabling the operator to point the sensor at an object of interest. Direct georeferencing systems (i.e., GNSS-aided inertial navigation systems) can also comprise an important part of the aircraft's payload.

2.1.7 Launch, Recovery, and Retrieval Equipment

For systems that are incapable of vertical takeoff and landing, additional equipment may be required. Launching equipment may consist of ramps, catapults, rubber bungees, compressed air, and/or rockets. Equipment for recoveries can consist of parachutes, large nets, or carousel apparatuses. Retrieval equipment is necessary for transporting the aircraft from its landing location to its launch point.

2.2 BACKGROUND ON FAA REGULATIONS

2.2.1 Certificate of Authorization (COA)

All UAS operations shown in this report were completed under an FAA Certificate of Waiver or Authorization (COA). A COA provides authorization to a public operator for a specific unmanned aircraft activity. At the beginning of this research project, a COA was the only legal method to operate a publically-owned UAS, such as aircraft owned by a DOT or public university. However, Part 107 rules were released in August of 2016, easing some of the requirements and necessary timelines for obtaining a COA. These new rules are discussed in the following section of this report, as it is anticipated that future sUAS inspections will be done primarily under Part 107.

In order to obtain a COA, a public entity must submit an application to the FAA. The FAA will conduct a formal review and has a goal to respond within 60 days. A COA application requires a description of the UAS and its performance characteristics, the location of the operation, a safety plan, any special equipment, and flight crew qualifications. Once granted, a COA will specify flight limitations and operational provisions. Typically, a COA will last for 2 years. OSU was granted a nationwide COA which will be discussed in greater detail in Chapter 3 of this report since it was used as authorization for the test inspections and flights were planned to meet its provisions.

The OSU COA, and, in general, most other COAs granted by the FAA (as well as Part 107) permit operation of a UAS in uncontrolled national airspace, known as Class G airspace (Figure 2.2). It may also allow operation in airspaces B through E by applying for a waiver, which may take up to 90 days to obtain. Class A airspace is between 18,000 and 60,000 ft. (5,500 and 18,300 m) above mean sea level (MSL). This elevation is so high that it would impact the performance of a sUAS. Class B through D airspace is based on the proximity and size of nearby airports with control towers. Class B airspace is for key airports with busy traffic; Class C is for moderate airports; and Class D is for small airports. Class E airspace is any controlled airspace that is not part of classes A through D.

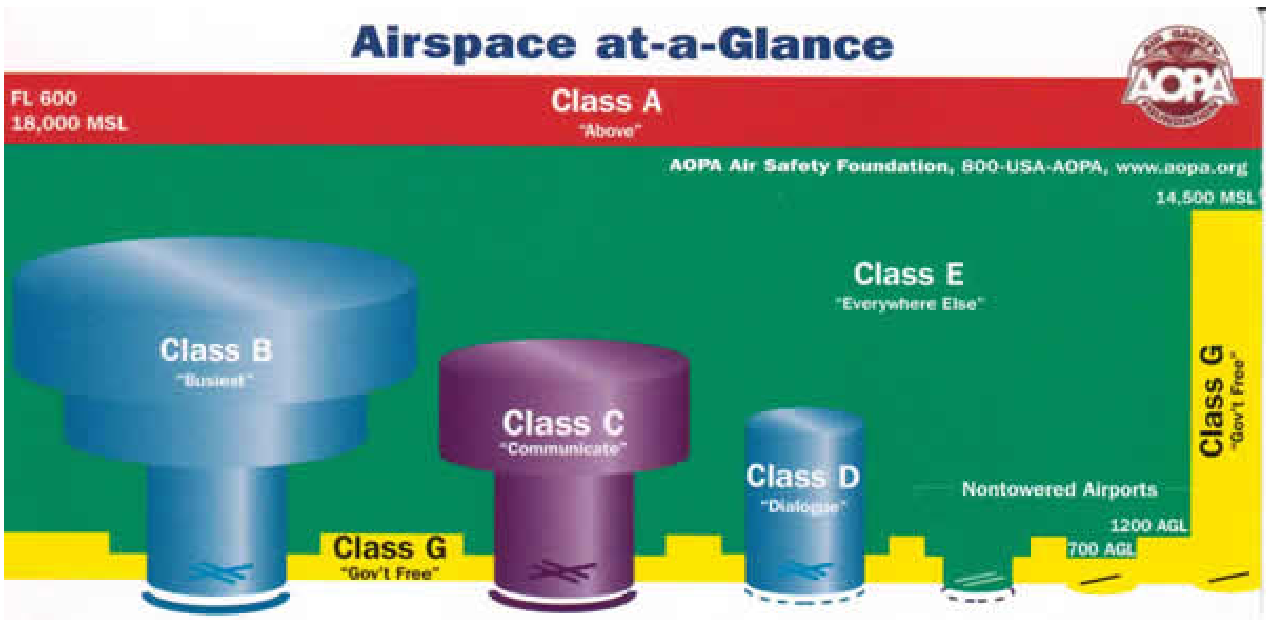


Figure 2.2: U.S. National airspace definitions

Although Figure 2.2 depicts that Class G airspace is generally limited to 1,200 or 700 ft. (370 or 210 m) above ground level (AGL) depending on its horizontal distance from an airport, a COA will typically also further restrict operations to be within 200 or 400 ft (60 or 120 m) AGL or above a structure.

In addition to airspace restrictions, a COA also requires that the aircraft be certified as airworthy and that it be registered with the FAA. In addition, the State of Oregon requires the aircraft to also be registered with the state.

2.2.2 Part 107 sUAS Rule

A number of technological and regulatory advancements occurred during the two-year span of this research project. On the regulatory side, the major change was the release by the FAA of the Small Unmanned Aircraft System Rule, officially Part 107 of Title 14 Code of Federal Regulations, 14 CFR (referred to hereafter simply as "Part 107"), which occurred on August 29, 2016. The primary impact of Part 107 was to facilitate commercial use of sUAS in the National Airspace. Prior to the official release of Part 107, non-public firms wishing to use UAS commercially were required to apply for a Part 333 exemption, with waiting times of up to six months or longer.

Importantly, "bridge inspection" is specifically mentioned in Part 107 as one of the "examples of possible sUAS operations that can be conducted under the framework in this rule" (FAA, 2016b). Among the specific changes brought about by Part 107, those listed in Table 2.2 were important in easing the requirements for commercial use of sUAS.

Table 2.2: Requirements Eased by Part 107, Facilitating Commercial Use of sUAS (<55 lb) in the National Airspace

Requirement	How eased by Part 107
Pilot's license	Pilot license (private or commercial) not required. However, a Remote Pilot Certificate is required. Must pass an initial aeronautical knowledge test or hold 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. Must also be vetted by TSA, and be ≥ 16 years old
Airworthiness certification	Not required (Remote Pilot must perform a preflight visual and operational check and must report to the FAA within 10 days any operation that results in at least serious injury, loss of consciousness, or property damage of at least $500)
Notice to Airmen (NOTAM)	Not required to be filed
Visual observer	Not required (although still recommended); the visual 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.
Airport contact	Not required in Class G (uncontrolled airspace) (however, still recommended best practice when operating near airport)
Educational use	Permitted

Notwithstanding the eased restrictions noted above, it is important to note that Part 107 is far from a "free for all" for anyone wishing to use sUAS commercially: a number of important regulations and restrictions remain in effect and must be adhered to for safe and legal flight. Table 2.3 (summarized from FAA, 2016b and FAA, 2016c) highlights just a few of the limitations that operators must be aware of when conducting a bridge inspection with a sUAS under Part 107.

Table 2.3: Operational Limitations in Effect Under Part 107

Operational limitations	Part 107 requirement
Operator	Operator (person manipulating the controls) must hold a Remote Pilot certificate or be under the direct supervision of someone holding a Remote Pilot Certificate who is designated as the Pilot in Command (PIC).
Aircraft registration	Aircraft must be registered
See and avoid	Visual line of sight (VLOS) only (without an exemption). First-person view cannot satisfy “see-and-avoid”
Operations	Daylight and civil twilight only
Visibility	Minimum weather visibility of 3 miles
Nonparticipating persons	May not operate over any persons not directly participating
Maximum altitude	Below 400 ft (120 m) AGL or within 400 ft (120 m) of a structure
Airspace	May only operate in Class G (uncontrolled) airspace without air traffic control (ATC) permission
Number of aircraft	A remote PIC cannot operate multiple UAS simultaneously
Accident reporting	Any accident resulting in serious injury, loss of consciousness, or property damage of at least $500 must be reported to the FAA within 10 days.

It should also be noted that Table 2.3 only attempts to summarize some of the key requirements and provisions of Part 107 with respect to bridge inspection applications; operators should carefully read and comply with all requirements of Part 107. Additionally, while privacy considerations are not specifically addressed by Part 107, many local municipalities have regulations related to privacy that may affect sUAS operations. Therefore, it is critical to know and adhere to any and all applicable state and local rules and regulations. Lastly, there are provisions for applying for a waiver to certain sUAS operating rules. Some of the sections of Part 107 that can be waived include the daylight operations and VLOS provisions.

2.3 PREVIOUS WORKS ON UAS FOR CIVIL ENGINEERING APPLICATIONS

2.3.1 Published Literature on UAS Structural Inspection

UAS technology is rapidly emerging and evolving, and the remote sensing data collected from UAS are proving valuable across a wide range of application areas, including agriculture, forestry, archaeology, engineering, and post-disaster response, to name just a few (e.g., Remondino et al., 2011; Adams et al., 2014). One emerging application that is garnering significant interest is the potential use of UAS technology for the inspection of existing infrastructure.

A number of fairly recent studies have been performed on using UAS for structural inspections. For example, in Germany, Hallermann and Morgenthal (2013) performed various UAS missions to simulate inspections. With the use of a small multicopter, the researchers were able to collect high resolution imagery of both industrial chimneys and tall historical buildings. Sa (2015) investigated the deploying of a sUAS to inspect tall structures that otherwise require extensive climbing equipment. Another goal of the research was to keep the aircraft a safe distance from the pole at all times even in high wind situations. To achieve this, a total station was set to track the aircraft at all times. By pairing the UAS with an on-site computer, the standoff distance was monitored and algorithms were set to create a virtual fence, which used the total station data as well as the GPS receiver onboard the aircraft to position the UAS.

An important criterion in evaluating the capabilities of UAS for inspections is whether they can provide comparable results to a physical inspection. Cracks and imperfections need to be detected and identified as if the inspector was within an arm's reach of the structure. Ellenberg (2014) searched for ways that UAS could be implemented for quantitative assessments. The researchers wanted to determine the size of cracks that RGB cameras mounted on an unmanned aircraft could detect from varying distances. Their research team concluded that cameras mounted on the unmanned aircraft could detect cracks of the magnitude of interest of visual inspections. The results also indicated that the use of UAS in automated defect and damage detection in civil infrastructure can lead to assessments that are more quantitative than human inspections. Eschmann (2013) used sUAS to scan infrastructure, including bridges and monuments at high resolutions for remote damage assessment and monitoring purposes. The technology's potential to also gather previously-inaccessible data allows the creation of a comprehensive database required for the monitoring of buildings. The inspection of infrastructures using aerial surveys thus provide a possible basis for new results in studies for condition detection and quality assurance regarding future non-destructive testing applications. Eschmann further showed that buildings and other structures could be captured at high resolution, and that the defects were readily visible.

The low cost operation of UAS allows for frequent flights to be performed in the same area. This multi-temporal capability enables time series-based structural health monitoring (SHM). Hallermann (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.

UAS technology appears well suited for bridge inspections, and numerous investigative studies have been completed recently. 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 remote sensing data that can be collected with a UAS. Khaloo et al. (2017) used computer vision techniques and imagery collected with a UAS to develop a high-resolution 3D model of the Placer River Trail Bridge in Alaska. The resulting 3D model helped with organizing the imagery collected during the remote inspection, and it assisted with noting the location of bridge defects. Escobar-Wolf et al. (2017) and Omar and Nehdi (2017) demonstrated the use of RGB and thermal cameras on a UAS for detecting concrete delaminations on bridge decks. Eschmann and Wundsam (2017) recommended flight patterns for the superstructure and substructure of a bridge, discussed the reconstruction of imagery collected during these flights into a 3D, georeferenced model of a bridge, and suggested how such a 3D model could function as the basemap for a web-based geographic information system (GIS) platform for presenting inspection results of a bridge. Dorafshan and Maguire (2017) tested the feasibility of using UAS for detecting cracks, both in real-time and by post-processing, in controlled conditions. They concluded that UAS are an assistive tool to the inspector to perform bridge inspection faster, cheaper, and without traffic closure.

Nearly all of the current literature is on the use of UAS for collecting remote sensing data of bridges in order to satisfy visual bridge inspection requirements. However, other technologies are emerging which will likely expand the usage of UAS for inspecting bridges in the near future. For example, Sanchez-Cuevas et al. (2017) presented the design of a multirotor UAS that can hold a fixed position while in contact with the structure. Such technology could be used for contacting a bridge for more in-depth inspections, such as for placing ultrasound sensors on the bridge in order to take measurements. In addition, other researchers and developers are currently working on enhancing aircraft to automatically “sense and avoid” obstacles without pilot intervention. Such improvements could greatly aid the ability of capturing high-resolution images of a bridge while flying in close proximity to its sub- and super-structure. Although obstacle avoidance technologies are improving and continuing to emerge, more work remains to make them function fully autonomously.

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 more detail in the following sections.

2.3.2 UAS for Other Transportation-related Activities

While the focus of this study is on UAS structural inspections, there are a vast number of other potential applications for sUAS in construction and transportation engineering. Table 2.4 lists a number of studies on these potential applications, as adapted from Mallela et al. (2017).

Table 2.4: Applications of sUAS in Construction and Transportation Engineering

Application	Examples of how it is used	Sources
Traffic Monitoring and Surveillance	Video collected from a camera on a UAS can be used for traffic surveillance, identifying traffic congestion, and counting traffic	Irizarry and Johnson (2014) [Georgia DOT]; Brooks et al. (2014) [Michigan DOT]; Puri (2005)
Structural Inspection	Sensors on a gimbal (e.g., RGB and thermal cameras) can be flown along structures for collecting high-resolution, close-up digital imagery and video. Enables remote, visual identifications of defects. Beneficial for remote inspection of areas that are dangerous for an inspector to physically occupy, such as bridges, towers, masts, etc.	Lovelace (2015) [Minnesota DOT]; Brooks et al. (2014) [Michigan DOT]; Eschmann et al. (2013); Hallermann and Morgenthal (2013); Khan (2015); Otero et al. (2015) [Florida DOT]; Gillins et al. (2016)
Construction Safety Inspection and Security	Safety managers at construction sites can use real-time video for quickly assessing current conditions both visually and audibly	Gheisari et al. (2014)
Roadside Condition Inventorying and Inspection	High-resolution aerial images and video can be used to assess the condition of roadway assets, determine the roadway's level of service, and set maintenance priorities	Barfuss et al. (2012); Hart and Gharaibeh (2011); Zhang (2008)
Topographic Surveying and Mapping	Overlapping aerial images from a UAS can be mosaicked and converted into orthophotos and 3D point clouds by Structure-from-Motion (SfM) algorithms; some UAS can also lift small lidar systems for surveying and mapping.	Judson (2013) [Ohio DOT]; Siebert and Teizer (2014); Brooks et al. (2015) [Michigan DOT]
Monitoring Construction Progress and Status	Aerial images collected from repeated flights can be used to monitor and document construction progress; images can also be used to detect any changes to areas neighboring a construction site.	Zollman et al. (2014); Lin et al. (2015)
Estimating Earthwork Volumes	Digital surface models (DSMs) can be constructed from overlapping aerial images or lidar. Volumes of stockpiles, earthwork, or complex objects can be computed using the DSM.	Siebert and Teizer (2014); Hugenholtz et al. (2015)
Identifying Potential Avalanches	Video from a UAS of snow gullies and chutes can be used to identify mountain roadways at risk of avalanches	McCormack (2008) [Washington DOT]
Monitoring Unstable Slopes	DSMs can be constructed from overlapping aerial images or lidar. DSMs from repetitive flights over an area can be differenced to find ground movements.	Lucieer et al. (2014); Niethammer et al. (2010)
Crash Reconstruction	At a crash scene, overlapping aerial images from a UAS can be mosaicked and converted into 3D point clouds by Structure-from-Motion (SfM) algorithms; could also survey scene using lidar on UAS	Brooks et al. (2015) [Michigan DOT]

2.3.3 Use of UAS in U.S. Departments of Transportation (DOTs)

The promise of the technology has spurred many DOTs to investigate the potential of applying UAS to solve construction and engineering problems. Dorafshan and Maguire (2017) showed that 29 state DOTs are currently using or have previously used UAS for accomplishing one or multiple tasks since 2002. The majority of topics that were or are being investigated by the DOTs can be classified into four main groups: traffic monitoring, structural inspection, construction site inspection, and other applications (e.g., surveying, aerial photography, landslide mapping, etc.). Table 2.5 summarizes some recent uses of UAS for accomplishing mission(s) at 15 DOTs. The following section provides more detail for each of the 15 DOTs summarized in Table 2.5. It is clear from this analysis that there is significant interest amongst DOTs on the use of UAS for improving safety, reducing cost, and increasing efficiency.

Table 2.5: Department of Transportation UAS Applications

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

2.3.3.1 Arkansas DOT

Arkansas DOT researchers 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). It should be noted, however, that this study was completed three years prior to the passage of the new Part 107 rules for sUAS operations.

2.3.3.2 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 if others are exploring this potential application of UAS (CTC, 2014).

2.3.3.3 Connecticut DOT

Connecticut DOT investigated the use of a multicopter UAS for inspecting the Gold Star Bridge of the Thames River, the longest bridge in Connecticut (Stacom 2016). The DOT hired a company to fly the UAS to specific spots for collecting imagery of the bridge, including its piers and deck underside. In a half-hour, the UAS collected imagery of portions of the bridge which would have taken hours using traditional equipment, such as bucket trucks and climbing equipment.

2.3.3.4 Florida DOT

Otero et al. (2015) have identified UAS as a potential tool to aid bridge inspectors. They were able to perform many indoor tests 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 and total inspection time.

Along with testing a UAS to collect imagery useful to a bridge inspector, the research group has also started 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. Their initial impressions of UAS were positive.

2.3.3.5 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.

2.3.3.6 Kansas DOT

McGuire et al. (2016) conducted a literature review, survey, and analysis on how UAS could potentially improve the safety, efficiency, and cost savings of the Kansas DOTs operations. The results indicated that UAS are particularly beneficial in terms of safety and from a technical point of view for bridge inspection, radio tower inspection, surveying, road mapping, high-mast light tower inspection, stockpile measurement, and aerial photography.

2.3.3.7 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.

2.3.3.8 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 a company 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 number of conclusions after the completion of the four inspections. They concluded that UAS are a suitable tool to perform:

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

- Pre-inspection surveys of the banks of the rivers, clearance heights, and location 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 GPS positioning and future studies would be enhanced if a UAS designed specifically for inspections was used.

- Tactile functions (e.g., cleaning, sounding, measuring, and testing) cannot be replicated using a UAS.

They also stated that safety risks associated with traffic control, such as working at height and in traffic, could be minimized with the use of UAS technology.

Wells and Lovelace (2017) expanded upon the prior work in Minnesota and tested UAS at several additional bridges, including: a large steel through arch, a steel high truss, a large corrugated steel culvert, and a movable steel truss. The report noted the importance of selecting an aircraft which can point its camera upwards to collect imagery of the underside of the bridge deck. It also estimated roughly a 66% cost savings when conducting a UAS inspection of a bridge as opposed to a traditional inspection. The majority of the savings were related to the reduction in cost of needing to use bucket trucks (i.e., snoopers) for accessing the bridge. Other benefits include reducing traffic control and lane closures which are required during traditional inspections. Minnesota plans to execute a third phase of the study in the next year on the use of UAS for inspecting tight and confined spaces, such as truss bridges, box girders, sewers, and tunnels.

2.3.3.9 Missouri DOT

The Missouri DOT, Shafer, Kline & Warren, and the University of Missouri-Kansas City tested the use of a multi-rotor UAS for inspecting a bridge in Missouri (Hernandez 2016). The crew identified challenges with camera exposure, aircraft stability when flying in close proximity to the bridge, and difficulties of operating the camera while simultaneously piloting the UAV. Hernandez (2016) developed an inspection platform allowing the use of dual remote control and manual control of camera exposure.

2.3.3.10 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 impact on the county and state if UAS were implemented.

2.3.3.11 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).

2.3.3.12 Texas DOT

Hart and Gharaibeh (2010) 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.

2.3.3.13 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, high-resolution aerial imagery from a UAS, the project documented the before, during and after stages of the construction of the Southern Parkway road near the new Saint George International airport. Researchers also photographed and classified wetland plant species.

2.3.3.14 Washington DOT

In support of Washington 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.

2.3.3.15 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.

2.4 FINDINGS OF THE LITERATURE REVIEW

It is clear that interest in UAS for structural inspections is already high and is continuing to grow, not only within the academic research community but also within state transportation agencies. Among the broad range of UAS types, those falling into the sUAS multicopter categories currently appear best suited for bridge inspections. Multicopters are capable of vertical takeoffs and landings, and they can hover alongside bridges and other structures in order to collect remote sensing data at specific locations. The ability to obtain high-resolution imagery and quantitative information from UAS for structural inspections has been demonstrated by numerous studies. Furthermore, while UAS cannot be used to satisfy every required element of a structural inspection, UAS can help facilitate enough elements to enable clear cost and safety benefits. Among the studies reviewed here, those by Otero et al. (2015), Lovelace (2015), and Wells and Lovelace (2017) are most closely related to the current work and contain a number of interesting findings.

Notwithstanding the many significant contributions of the literature published to date, it is evident that gaps remain in the current state of knowledge associated with UAS bridge 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 with a DOT bridge inspection program. Additional work also remains to be done to quantify potential cost savings of implementing a UAS bridge inspection program. Specific questions that need to be addressed include:

- What are the required elements of a safety plan for UAS bridge inspection within a state DOT?
- What end-to-end operational procedures and workflows must be followed by bridge inspectors, UAS pilots, 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 a detailed cost-benefit analysis?
- How do new and proposed Federal and State regulations related to UAS impact operational use by a DOT?

The remaining portions of this report will be aimed at addressing these questions and challenges.

3.0 EQUIPMENT AND METHODOLOGY

In order to research the capabilities and limitations of using sUAS for inspecting structures, equipment was acquired and a methodology was developed to conduct several test sUAS inspections of bridges and wireless communication towers in Oregon. This chapter provides details on the equipment and proposed methods for conducting the test inspections. The following chapter shows results on the implementation of the equipment and proposed methods at five bridge sites and four tower sites.

3.1 EQUIPMENT

3.1.1 Selection of the sUAS

As stated in the previous chapter, there are a large number of available systems for use. However, after reviewing the literature and the technical capabilities of the systems on the market today, it became apparent that the sUAS should ideally have the following characteristics for structural inspections:

1. A multirotor design, enabling vertical takeoff and landing, as well as the ability to hover in place during flight; such a system will enable flight missions where close-up imagery can be collected along structures;

2. An enhanced ability (i.e., by using sensors) to fly close to structures while maintaining a fixed, safe stand-off distance;

3. An inclusion of flight planning software for the GCS, ideally designed for inspection work;

4. A stabilizing gimbal that can alter the camera pointing angle to any vertical angle (i.e., ± 90 degrees), such as:

    a. nadir (straight downward) to capture imagery of the top of the structure or its surroundings
    b. forward to capture oblique imagery of the sides of the super- and sub-structure
    c. zenith (upward) to capture overhead imagery while flying underneath the structure;

5. A camera equipped with an optical zoom for capturing high-resolution imagery while at a safe standoff distance;

6. First-person view capabilities to assist the pilot by providing enhanced perspective of the proximity of the aircraft to the structure and to enable a determination of whether or not the acquired imagery is satisfactory during the remote inspection;

7. A headlamp for providing light to features on an element of the structure in the shadows

Given the above list, three different and available sUAS that met FAA rules at the time of the flights were used in the test inspections documented in this report:

- DJI Phantom 3 Pro quadcopter
- senseFly albris quadcopter
- DJI S900 hexacopter with Pixhawk 2.0 flight controller

Unfortunately, none of the three selected aircraft met every item on the above list, but testing each one allowed comparison and evaluation of the relative importance of each of the items.

Despite its relatively low cost as compared with the other systems, the Phantom 3 Pro is a turn-key system that has most of the characteristics given in the above list. However, its camera is beneath the body of the aircraft, and, therefore, it cannot capture zenith imagery while flying underneath the structure. The Phantom 3 Pro was used in the first test inspection of the Independence Bridge (see results in Chapter 4). The unmanned aircraft is equipped with a 4K HD camera and first-person view video can be broadcast to a mini tablet attached to the top of a radio frequency flight controller (Figure 3.1).

Figure 3.1: DJI Phantom 3 Pro quadcopter with a 4K HD camera (left) and GCS with pilot (right)

After the initial test inspection, in December of 2015, the senseFly albris was acquired, because it appeared particularly well suited for inspecting structures. Its primary sensors include an HD video camera, 38 megapixel still camera, and a thermal infrared camera. These sensors are installed on a front-mounted camera head that can be rotated in flight 180° from nadir to zenith (or any desired angle in between), such that capturing data on the undersides of objects is possible (Figure 3.2). In addition to the three cameras on the head of the albris, it is also equipped with five ultra-wide navigation cameras (navcams) and five ultrasonic sensors (Figure 3.3). Pairs of navcams and ultrasonic sensors are distributed on all sides of the aircraft. The pilot can switch the monitor to view each navcam during flight for first-person viewing, and the ultrasonic sensors can be set to provide a high-pitch chirping sound to warn the pilot when the aircraft is within a preset distance of the structure. In addition, using one ultrasonic sensor, the albris also has the capability to maneuver up-and-down and side-to-side along a structure while holding a locked stand-off distance. Another benefit is that the flight planning software, *eMotion X* (recently superseded by a newer version, *eMotion 3*), provided with the albris, is designed to facilitate inspections.

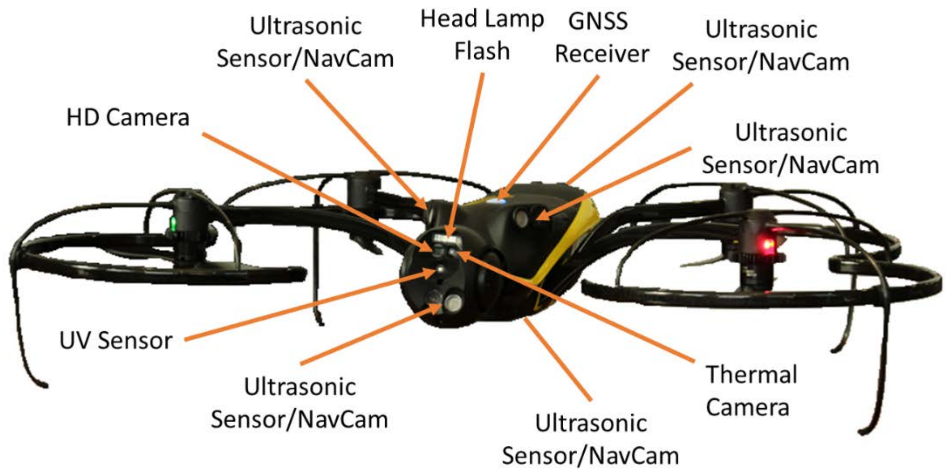


Figure 3.2: Orientation of cameras, navcams, and ultrasonic on the senseFly albris

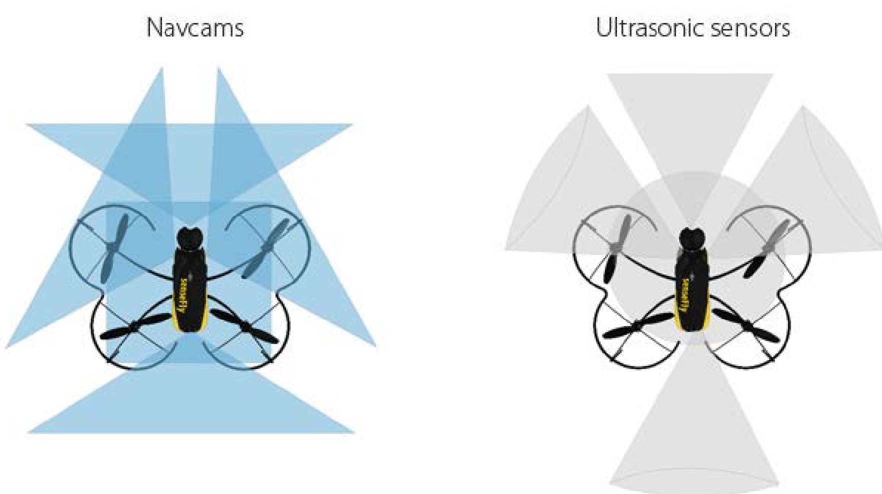


Figure 3.3: Pairs of navcams and ultrasonic sensors placed on the albris for assisting the UAS operator in avoiding obstacles during flights.

The albris has a number of helpful features for inspection and was primarily used for most of the test inspections documented in this report. However, none of its cameras have optical zoom capabilities. As a result, the albris must be flown in very close proximity to the structure to obtain the desired high-resolution imagery. It is possible that safer operations could be accomplished by using an aircraft equipped with a camera with an optical zoom. Using a zoom, high-resolution imagery could be collected while flying a wider standoff distance from the structure. To investigate this idea, a lightweight camera with a 30x optical zoom (Sony WX500) camera was purchased (Figure 3.4). This camera was mounted on a custom hexacopter built with a DJI S900 frame (Figure 3.5), and it was tested by collecting imagery of the St. Johns bridge (see Chapter 4). The custom hexacopter has an open-source Pixhawk 2.0 flight controller.

Figure 3.4: Sony WX500 camera with 30x optical zoom

Figure 3.5: Custom DJI S900 hexacopter flying with a Sony a5000 camera

3.1.2 Setup of the Ground Control Station

The components of the GCS (i.e., hand-held controllers, software) varied greatly depending on which aircraft was used. The typical setup used by the project team, as shown in Figure 3.6, included a collapsible music stand, Dell XPS 13-inch laptop, an external/backup 12-volt power supply for the laptop, and a sunshade to prevent excessive glare on laptop screen. It is highly recommended to have a backup power supply connect to the control station to ensure it does not lose power during flight. Table 3.1 shows the different flight control software required for each aircraft used in the various inspections.

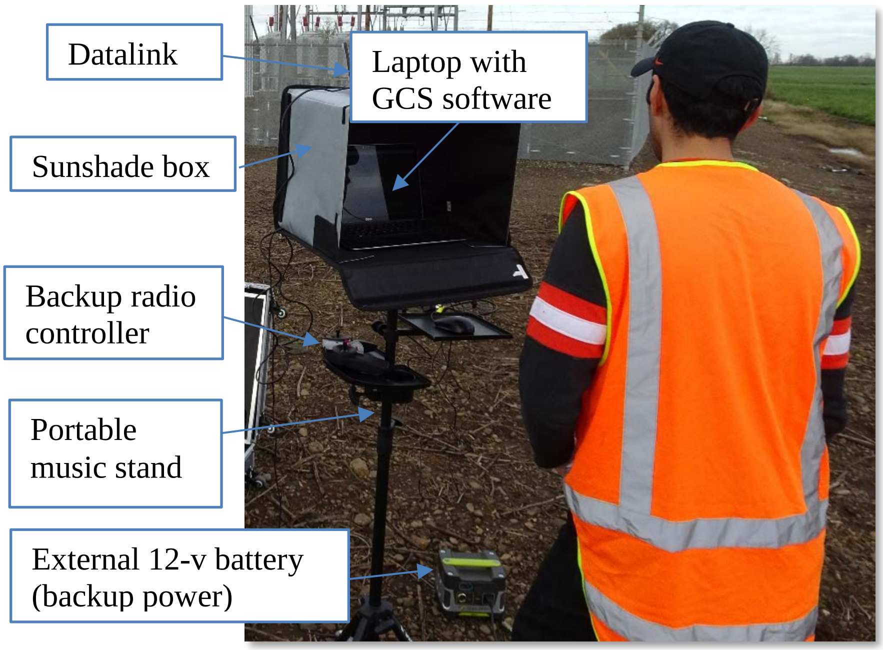


Figure 3.6: Typical GCS setup for the pilot during each UAS inspection.

Table 3.1: Corresponding Flight Controlling Software Used for Each Airframe During Inspections

Unmanned Aircraft	Flight Controller Software
DJI S900	ArduPilot MissionPlanner
senseFly albris	eMotion X (recently replaced with eMotion 3)
DJI Phantom Pro 3	DJIFlightPlanner

Another important aspect to setting up the GCS is selecting a location with the best vantage point of the aircraft during flight. Multiple setups may be required to inspect an entire structure while maintaining visual line-of-sight with the aircraft. When selecting these locations, areas with tall vegetation, slick surfaces, and standing water should be avoided.

3.1.3 Ground Control Survey Equipment

In addition to the UAS, other surveying equipment was used to establish ground control points (GCPs) for some of the test UAS inspections. As discussed in more detail in the following section of this chapter, overlapping 2D imagery can be collected of a structure during an inspection. If this imagery is collected in a systematic and comprehensive manner, structure-from-motion (SfM) software (e.g., *Agisoft Photoscan* or *Pix4DMapper*) can be used to derive a 3D point cloud or 3D model of the structure. Additional derivative products of this point cloud include ortho-rectified images, an orthophoto of the inspection site, and a digital terrain model.

The coordinates of a point cloud from SfM software will be output in an arbitrary coordinate system unless the UAS carries equipment capable of directly georeferencing the imagery, or if GCPs are established prior to the acquisition of the imagery. Direct georeferencing technology generally adds significantly to the weight, cost, and power requirements of the unmanned aircraft and, therefore, was not utilized on the sUAS utilized in the tests. Rather, at some of the sites, GCPs were established.

To establish the GCPs for those inspections where a 3D model of the structure was desired (as shown in Chapter 4), temporary 1-meter square aerial targets with black and white crosses were distributed throughout the site and were nailed in the ground (Figure 3.7). In addition, stable features which could be distinguished in the imagery were identified and used as GCPs (e.g., sidewalk joints, large bolt heads on the structures, paint stripes, etc.).

Afterwards, the geodetic coordinates of the GCPs were derived utilizing a dual-frequency, Leica GS14 GNSS rover receiving full network corrections from ODOT's Oregon Real-time GNSS Network (ORGN). After making several independent real-time kinematic (RTK) GNSS observations of each GCP with the rover, a reflector was set up over each GCP. Then, multiple observations were made with a Leica Viva TS15 total station set up over a minimum of two different locations. Finally, the RTK GNSS and total station measurements were added to a survey network, and this network was adjusted by least squares to derive most-probable geodetic coordinates for each GCP. These coordinates were later used as control in order to georeference the SfM point clouds from the test inspections.

Figure 3.7: Establishment of ground control points by conducting a survey of temporary aerial targets using a dual-frequency GNSS receiver

3.2 WORKFLOW FOR UAS INSPECTION

The UAS inspection workflow had seven general phases, designed to ensure a safe, legal, and effective UAS-based inspection: (1) perform reconnaissance; (2) plan for safe operations; (3) submit notifications, agreements, and/or FAA compliance documents; (4) plan the flights; (5) conduct a preliminary flight; (6) acquire remote sensing data for the inspection, and (7) perform post-processing. Each of these phases is summarized in Figure 3.8 and discussed in more detail below.

3.2.1 Reconnaissance

The first phase was to evaluate the project site in order to ensure safe and legal flight operations. After identifying a structure for UAS inspection, it was important to examine real property rights, such as the ownership, rights-of-way, and/or any easements of the structure and its underlying land. UAS flights were not performed above real property without permission from the owner. ODOT provided permission for UAS operations prior to flying above any real property (e.g., bridges, towers, highway routes, etc.) it manages. Permission from others with rights to the property (if any) were also obtained.

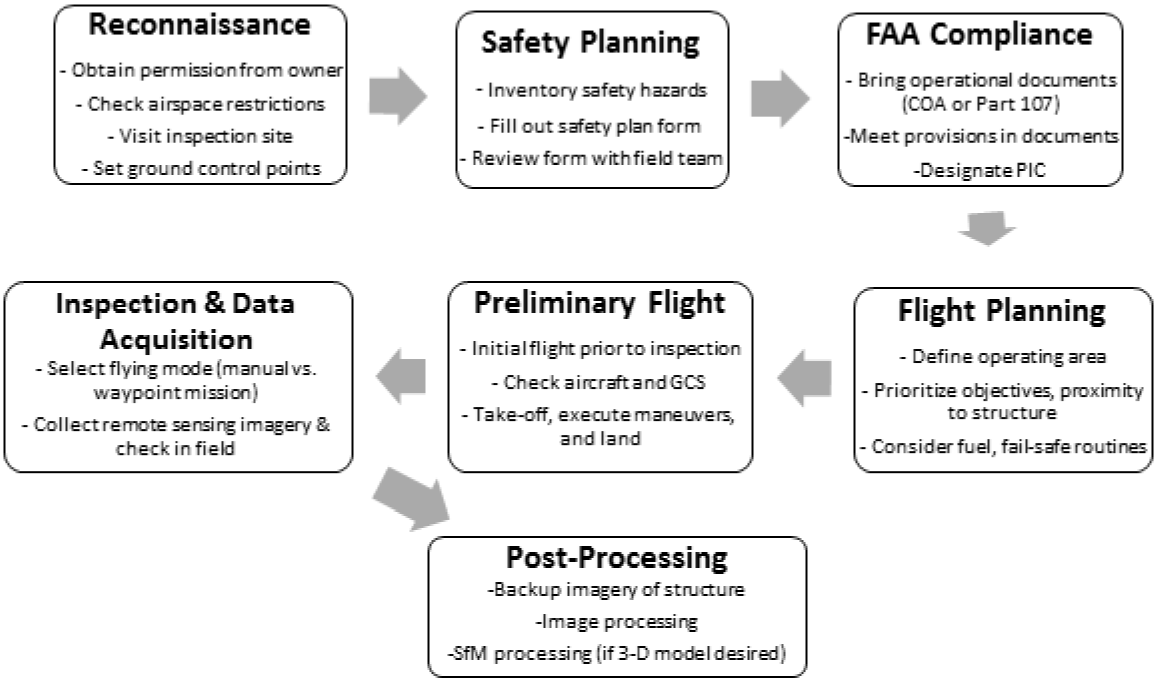


Figure 3.8: Steps in a UAS inspection

In addition to investigating property rights, the airspace classifications near and above the structure were examined to ensure compliance with FAA restrictions. Although the FAA released the Part 107 rules in the middle of this research project, all UAS operations shown in this report were completed under a COA from the FAA and not under Part 107 rules. Since flights were performed under a COA, details on COA provisions are given below; however, because future UAS inspections will likely be conducted under Part 107 rules, the authors also noted where any of the COA provisions are *not* required when operating under the newer Part 107 rules. Under the COAs utilized for testing, operations in Class G (i.e., uncontrolled) airspace were allowed without Air Traffic Control (ATC) permission. Thus, test inspection sites were purposefully chosen in Class G airspace. (Note that under Part 107, UAS operations in Class G airspace are also allowed without ATC permission.)

As per Figure 2.2, although Class G airspace may extend as much as 1200 ft. (370 m) above ground level, the COA restricted flights to a lower altitude, such as 200 or 400 ft. (60 or 120 m). (Note that Part 107 rules restrict flights to within 400 ft. above ground level or 400 ft. of a structure.)

Unlike Part 107 rules, the COA required notification to the managers of all airports and heliports within a certain distance of the operations (e.g., 2 to 5 nautical miles) prior to the flights, even if the operations were in Class G airspace. FAA sectional charts were researched for identifying the airspace and if airports and heliports were within the specified distance. The team made use of *Drone Complier*, online software for viewing the detailed information in FAA sectional charts referenced on top of aerial imagery of the project site. As an example, Figure 3.9 shows a waypoint at a UAS test flight of a tower on a sectional chart near Corvallis, Oregon. As shown, the waypoint was within 3.2 nautical miles of the Corvallis airport; this airport was notified prior to the intended UAS flight operations. A "letter of agreement" was developed and sent to such nearby airports in order to notify them of intended UAS operations. An example of such a letter is given in Appendix B.

The FAA sectional charts were also studied to determine if the operational area was within Military Training Routes (MTRs), Restricted Areas, Prohibited Areas, or Special Flight Rule Areas. In the event the operational area overlapped an MTR, the scheduling agency was contacted to coordinate and de-conflict. Notices to Airmen were also studied to ensure the flights avoided identified areas that may restrict operations. Note restrictions are also often placed in proximity to power plants, electric substations, dams, wind farms, oil refineries, industrial complexes, national parks, Disney resorts, stadiums, emergency services, and military or other federal facilities.

During this phase, an early field visit to the project site was also completed in order to begin planning the flights, noting any obstacles, and identifying other potential challenges with the flights. During the field visit, the reconnaissance team identified areas for safe take-offs and landings. Ideal areas are flat, free of vegetation, and distant from hazards such as water (unless, of course, the aircraft is capable of landing in the water). The field reconnaissance team also note any potential obstructions in the flight paths, such as tree limbs, overhead power lines, and towers which may block the vehicle. It was also important for the field team to consider possible jamming of the data link signals between the ground station and the aircraft. Wireless communication towers near the project site may broadcast signals at the same frequency as the GCS of the UAS. A smart phone app (e.g., Wifi Analyzer) was used for detecting the frequency of signals broadcasted near the inspection site; however, a spectrum analyzer was used when flying at a site with numerous wireless communication towers (see Chapter 4).

For inspections where a 3D point cloud or orthophoto of the structure was desired, the field reconnaissance team also established ground control points (GCPs) during this phase of the project. As discussed later in this report, Structure-from-Motion (SfM) software programs can reconstruct 3D models from overlapping digital photographs. However, SfM outputs results in an arbitrary coordinate system. Since the selected sUAS were not capable of directly georeferencing the remote sensing data, GCPs were needed for transforming the arbitrary coordinates into georeferenced coordinates. GCPs were established by conducting a survey with a total station and/or real-time kinematic GPS equipment of distinctive features in the project area which can be easily identified in the digital photos. Examples of distinctive features that were surveyed included road striping, placement of temporary aerial targets (Figure 3.7), sidewalk edges, and the center of large bolt heads at bridge joints.

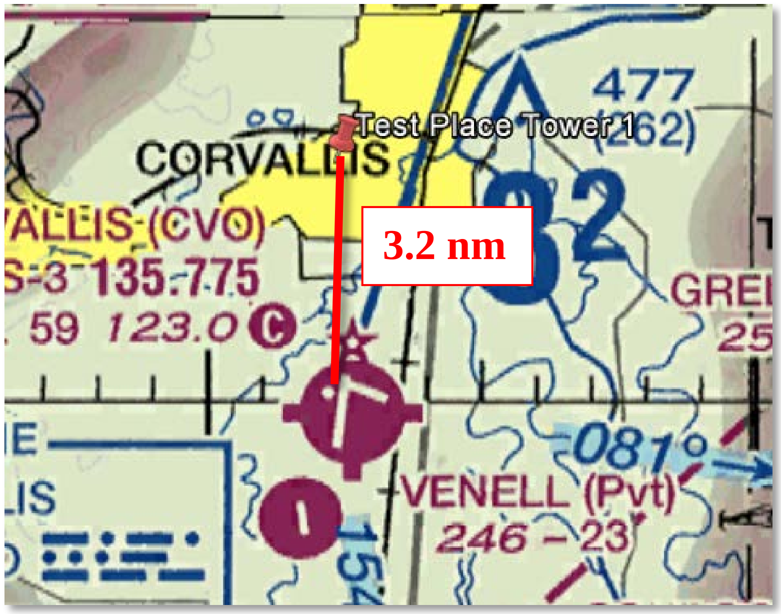


Figure 3.9: Example FAA sectional chart with depiction of the distance from a UAS test flight site to the Corvallis Airport

3.2.2 Safety Planning

Safety is paramount, and the next phase was to develop and document a safety plan for the project. This plan was communicated with all people involved in the project at the start of the operations. In coordination with ODOT, a Safety Plan Form was developed which was filled out and signed by the ODOT UAS operations manager. Only when signed has ODOT accepted the form and given permission for the UAS operations. An example of the Safety Plan Form, with blanks filled in for an inspection of a communication tower, is provided in Appendix A. In addition to identifying the location of the operations, the form requires an inventory of safety hazards, such as identification of traffic, confined spaces, tripping and weather hazards, heavy lifting, and more. After identifying these hazards, the form next requires comments on a plan for mitigation of the hazards. Just prior to beginning the flights, the safety plan was again reviewed with the project team.

3.2.3 FAA Compliance Documents, Agreements, Notifications

In addition to filling in the blanks for safety concerns, the Safety Plan Form also provided blanks that were filled in regarding FAA compliance. These fields were meant to ensure legal operations. For example, the form required designation of the Pilot-In-Command, Visual Observer, the COA number, and the contact information and the radio frequency of air traffic controls for nearby airports and heliports.

OSU was granted a nationwide COA for its flight operations (No. 2016-WSA-101-COA). In addition, all aircraft managed by the project team were registered with the FAA and with the State of Oregon, and they were certified by OSU as airworthy. A copy of the nationwide COA is given in Appendix C. The COA and all documents needed to operate the UAS and conduct operations in accordance with the conditions and limitations stated in the COA are referred to as the operating documents. The UAS operational team is required to meet all provisions stated in the operational documents. Among many items, the COA lists five standard provisions, and gives numerous additional special provisions and limitations which must be met during all operations.

Some of the provisions are discussed in greater detail below, and the reader is encouraged to review all of the provisions in Appendix C to gain an enhanced understanding of the legal restrictions on UAS operations when operating under a COA. Since the provisions in the COA granted to OSU are relatively "typical," it is highly likely that others who desire to conduct a UAS-based structural inspection under a COA will face similar provisions. Hence, the information below is given in detail because it is meant to raise awareness of the types of provisions and restrictions that must be met when operating under a COA. Nonetheless, depending on a specific COA, it is possible that other atypical provisions may be specified.

The provisions of the OSU COA state that the operational team must read it, and a copy of the COA must be made immediately available to all operational personnel or upon request by an administrator or law enforcement officer. To meet the provisions, a copy of the COA was placed in the UAS equipment case and in the vehicle. A copy of the COA was also attached to the Safety Plan Form, and both documents were submitted to ODOT. The OSU project team assigned the Pilot-in-Command (PIC) as the person responsible for keeping a Safety Plan Form and COA nearby during the operation, and the PIC ensured the team read and understood these documents prior to operations.

Other provisions required designation of a PIC and a Visual Observer (VO). (Note that Part 107 rules do not require use of a VO.) Unlike Part 107 rules, the COA provisions allowed government entities to develop an internal policy for PIC certification. The COA provisions also stated that the PIC must demonstrate the ability to safely operate the UAS in a manner consistent with how the UAS will be operated under a COA. Accordingly, OSU has developed a policy for training and certifying the PIC, and only OSU-certified personnel were allowed to serve as the PIC on the UAS operations. In addition to these provisions, the COA also stated the following regarding the PIC and VO:

- The aircraft must always be within visual line of sight (VLOS) of the PIC or VO
- The PIC or VO may not use any device (e.g., binoculars) other than corrective lenses while satisfying VLOS requirements
- Prior to each flight, the PIC must conduct a pre-flight inspection of the UAS
- When operating in the vicinity of an airport without an air traffic control tower, the PIC must announce operations on appropriate frequencies alerting manned pilots of UAS operations.
- The VO will notify the PIC immediately if he/she loses sight of the aircraft. If the aircraft is not visually reacquired promptly, the PIC will execute "fail-safe" or lost link procedures.

- The PIC is responsible for identifying the appropriate Air Traffic Control jurisdiction to the operational area defined by the Notice to Airmen (NOTAM).

- The PIC must abort the flight in the event of emergencies or flight conditions that could be a risk to persons and property within the operating area.

- The PIC and VO(s) must be positioned such that they can maintain sufficient visual contact with the aircraft in order to determine its attitude, altitude, and direction of flight.

- The PIC is responsible to ensure that the aircraft remains within the defined operating area, as defined below. “Out of Sight,” or “Behind the Obstruction” flight operations are prohibited.

Unlike Part 107 rules, the COA also listed additional requirements for coordinating with Air Traffic Control. As stated earlier, one requirement is that airports and heliports within a certain distance of the operational area are notified of the UAS flights. For the OSU nationwide COA, all of the following specific types of airports and heliports within the following prescribed distance to the airport reference point (ARP) were notified:

- 5 nautical miles from an airport having an operational control tower

- 3 nautical miles from an airport having a published instrument flight procedure, but not having an operational control tower

- 2 nautical miles from an airport having a published instrument flight procedure or an operational tower

- 2 nautical miles from a heliport

Prior to any UAS flights, all airports and heliports within the above prescribed distances of the intended flights were notified and a Letter of Agreement was sent for signature.

Unlike Part 107 rules, the COA also required that a Notice to Airmen (NOTAM) was issued prior to conducting UAS operations. This was accomplished through the proponent’s local base operations or NOTAM issuing authority, or by contacting the NOTAM Flight Service Station at 1-877-4-US-NTMS. A NOTAM was issued 24 to 72 hours in advance of UAS operations. The Research Office at OSU ensured a NOTAM was filed in a timely manner prior to operations for this research project. If for some reason the flights were not conducted, of if the operations were completed ahead of schedule, then the NOTAM was canceled.

In addition to the provisions discussed above which must be met prior to conducting any flights, the COA also lists requirements for planning the flights, and it lists operational and emergency procedures when performing the flights. In order to comply with all terms of the COA, these additional requirements and provisions were met. Since these items must be met during the flight planning and data acquisition phases of the mission, these additional requirements and provisions are discussed in the subsequent sections of this report.

3.2.4 Flight Planning

When planning flights, the operational team must first understand the flight limitations stated in the COA. The following list summarizes important limitations stated in the OSU nationwide COA. During flight planning, the following limitations were considered and met:

- Only sUAS operations are allowed during daytime conditions within Class G airspace at or below 400 feet above ground level.

- The aircraft must be within VLOS of the PIC and VO at all times.

- UAS flight operations are restricted to within a “defined operating area,” as identified when issuing a NOTAM. A “defined operating area” is described as a location identified by a Very High Frequency Omnidirectional Range (VOR) Radial/Distance Measuring Equipment (DME) fix. This location must have a defined perimeter that is no larger than that where visual line of sight with the aircraft can be maintained and a defined operational ceiling at or below 400 feet above the ground.

- The aircraft may not be operated less than 500 feet below or less than 2,000 feet horizontally from a cloud or when visibility is less than 3 statute miles from the PIC.

- The UAS may not be operated by the PIC from any moving vehicle or vessel without additional permission from the FAA.

- All flight operations must be conducted at least 500 feet from all *nonparticipating* persons, vessels, vehicles, and structures. (Note that if given permission, then the persons, vessel, vehicle, and/or structure is *participating* in the flight and this provision does not apply.)

After ensuring compliance with the provisions in the COA, a number of additional considerations were taken into account during flight planning, based on the size of the site or structure for inspection, flying height, standoff distance, obstacles, battery capacity and endurance of the aircraft, fail-safe features of the system, etc. Table 3.2 lists important questions that were considered while planning safe and efficient flights. The table also discusses each question and offers recommendations.

In addition to the considerations discussed in Table 3.2, mission planning software was used to develop specific, systematic flight plans. For enhanced safety, some software allows the planner to specify a “boundary” around the defined operating area. If the aircraft attempts to fly outside of this boundary, the GCS will send a fail-safe signal. For example, Figure 3.10 shows a “donut” boundary that was utilized in eMotion X when planning flights with the senseFly albris. The donut encircles the defined operating area, and its radius and thickness can be specified by the planner. If the aircraft reaches the inner ring of the donut, the GCS will send a “return-to-home” signal to attempt to recover the aircraft. If for some reason it reaches the outer ring of the donut, the GCS will send the “land-now” signal. The project team applied this donut around the defined operating area prior to all flights with the albris to reduce the risk for the aircraft to fly away unexpectedly. An equivalent boundary fence was used when planning flights with the other sUAS.

Table 3.2: Important Considerations When Planning Flights with a UAS

Consideration	Discussion	Recommendations
Which feature(s) will be inspected with a UAS?	The specific objectives and goals of the project should be communicated to the flight planner(s) at the start of the project.	Prioritize the objectives, then plan the flights accordingly. Sometimes, entire missions fail if a crash occurs during the flight of a lower-priority objective. The highest priority objectives should be done first to maximize the likelihood of mission success.
How close should the aircraft fly to the feature(s)?	Flying close to a feature maximizes the resolution of the imagery collected with a UAS. In some cases, very highly resolute images are required. However, flying very close also increases the likelihood of crashing into the feature, especially during gusts of strong wind. GPS signals greatly assist the pilot during flights. Unfortunately, large, overhead objects may block or delay GPS signals.	If wind is not present, our experience is that flights can be safely conducted up to roughly 3 meters from the feature. If needing to fly closer (or even underneath a feature), then try to use other sensors than GPS for flight assistance—such as ultrasonic sensors. Position a visual observer such that he/she has a clear view of the distance between the feature and the aircraft in order to warn the pilot. The pilot should use the first-person view video on a monitor to gain improved perspective of the distance of the aircraft from the feature.
Is there sufficient battery capacity for the flight?	Generally, most multicopters have limited endurance and batteries need to be changed often. Due to their lightweight construction and performance, lithium polymer batteries (LiPo's) are commonly used. LiPo's should not be drained below 15% of their capacity, or they will be damaged. Therefore, an aircraft must be safely landed in time to change batteries prior to reaching such a low capacity.	The flight planner should have clear understanding of the typical endurance time of the aircraft, and whether or not the aircraft will attempt to return to home or land itself if it reaches low battery capacity. Charge all batteries either the day before or on the day of the operations. Log the total flight time for each battery each time it is used in order to monitor its performance. Make sure the aircraft can safely return to the landing area each time a battery needs to be replaced. Avoid draining the battery to 15% capacity and plan the flights so that the pilot has extra time as a buffer. Store batteries in a cool, dry place at 3.8-3.85V per cell (do not store them fully charged).

Consideration	Discussion	Recommendations
Where is the “home” point located and why is it important?	As a fail-safe precaution, many ground control stations will define a “home” point. If the ground control station issues a “return-to-home” signal to the aircraft, the aircraft will attempt to return and even land at this point. Depending on the system, the home point may be set where the aircraft was turned on, at its launching point, or at a point specified by the operator.	Set the home point at a location where the aircraft can safely and easily land, if needed. Inform the observers of the location of the home point prior to the flights.
What happens if the ground control station issues a fail-safe signal to the aircraft?	Systems have a variety of fail-safe procedures meant to reduce the likelihood of a crash. The signals may be sent if the aircraft attempts to fly outside a specified boundary area, if data link is lost, or if an onboard component fails. Common fail-safe signals are “return-to-home” and “land-now.” As these names imply, the aircraft will attempt to return to its home point or will attempt to lower itself straight downward in order to land when receiving these signals.	Make sure the planner and operator have a clear understanding of the fail-safe protocols on the UAS and know how to over-ride the signals if needed. Plan flights so that the aircraft can safely “return-to-home” as needed when executing a fail-safe routine. For example, the albris will fly up or down to a user-specified altitude before attempting to fly home. Generally, setting the altitude above all obstacles (e.g., a tower) will prevent collisions when returning home. However, if flying underneath a vertical obstruction (e.g., bridge, tree), it would be safer to set the altitude below the obstruction. Flights should be planned differently when flying above or beneath obstacles.
What should be done if the aircraft doesn’t respond to the ground control station?	In some cases, the aircraft may lose its link with the ground control station, and it may not respond to fail-safe signals. It is important to have an emergency procedure planned for such circumstances.	Make sure the planner, operator, and observers have a clear understanding of the emergency protocols. For the albris, a secondary radio flight controller is available and can be turned on to override the ground control station. This controller should be handy, and the operator should be familiar with how to fly the aircraft with it during an emergency.

The mission planning software can also be used to set up waypoint missions for systematic flights and data acquisition along specific flight paths. Depending on the complexity of the project, the planner may decide to plan waypoint missions in the office, then refine these plans in the field. More discussion on waypoint missions and the advantages are given below.

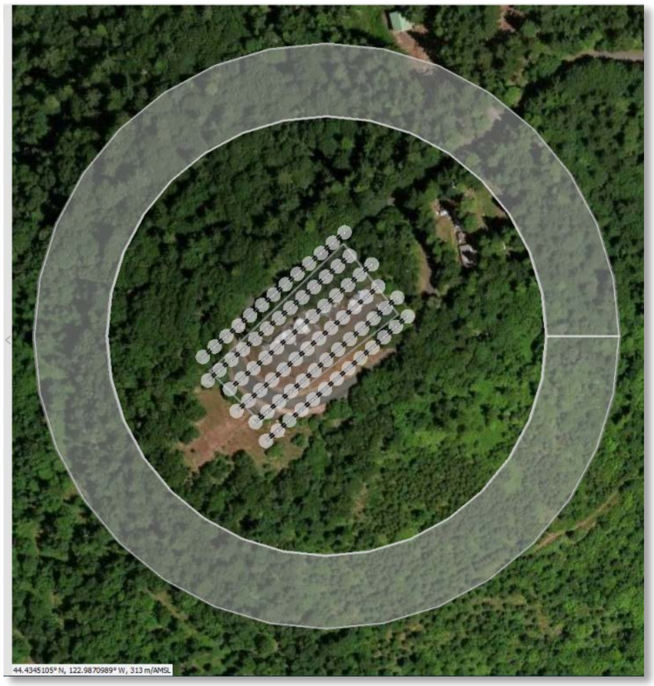


Figure 3.10: Example "donut" for specifying a boundary around the defined operating area. If the UAS reaches the inner ring of the donut, the GCS will send a "return-to-home" safe signal to the aircraft. If it reaches the outer ring of the donut, the GCS will send

3.2.5 Preliminary Flight

The operating documents typically require a preliminary flight and aircraft inspection before executing the UAS mission. This initial flight was conducted each day of an inspection, and it was helpful for ensuring that the system was functioning well and safely, and that the aircraft was responding correctly to the signals from the ground control station. The preliminary flight was less than 5 minutes and generally simply involved a take-off, a few maneuvers (e.g., roll, pitch, and thrust) in response to signals from the GCS, and then a landing. The operator checked that the gauges were displaying properly on the GCS. All items on the standard preflight checklist from the operating documents were then addressed and filled out.

3.2.6 Data Acquisition for Inspection

If the preliminary flight is successful, the next phase is to perform the full UAS flights in order to acquire the data in support of an inspection. An aircraft may carry a variety of different cameras for its payload, ranging from visible to hyperspectral cameras capable of collecting imagery in numerous, narrow, contiguous spectral channels, typically extending through the visible and near infrared portions of the electromagnetic spectrum. As examples, in addition to acquiring HD video, the albris is capable of acquiring high-resolution, three-band (R,G,B) visible-light spectrum imagery (e.g., Figure 3.11) and thermal infrared imagery (e.g., Figure 3.12) simultaneously. The visible-light imagery is helpful for identifying visible defects. However, some defects cannot be easily identified in the visible light spectrum, and thermal imaging can be useful for structural inspection.

This section discusses three different methods for flying the aircraft and triggering the cameras in order to acquire the imagery for inspection: 1) manual flights, 2) flights with sensor-assistance, and 3) waypoint-assisted flights. Prior to discussing and defining each of the three flight procedural methods, it is important to first identify operational and emergency procedures stipulated in the OSU nationwide COA. These COA provisions must be met during all UAS operations.

Figure 3.11: Example photo taken with a visible-spectrum camera on a UAS of a bridge steel-to-concrete bearing connection; note the possible leaking joint at this connection

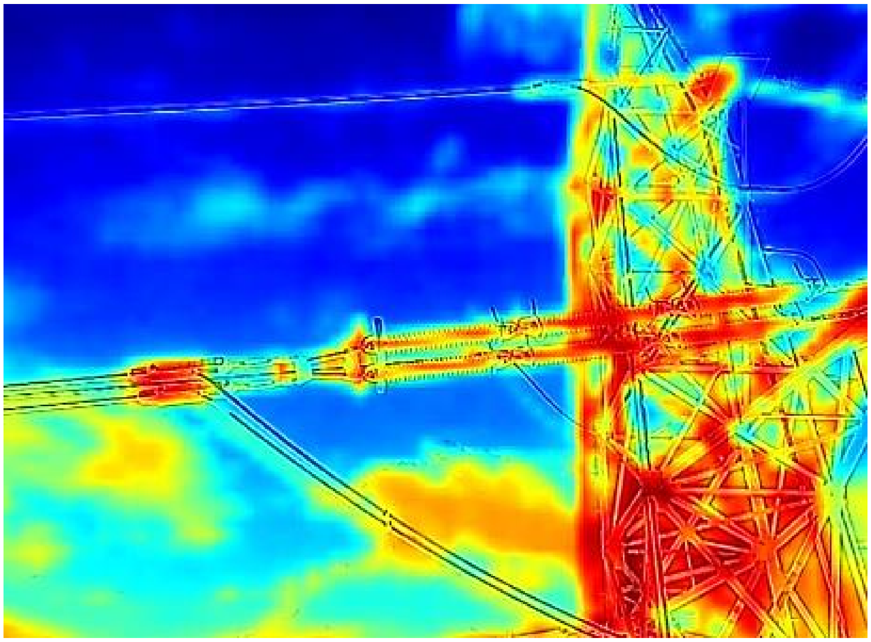


Figure 3.12: Example photo of a transmission tower taken with the thermal camera on the albris

3.2.6.1 Operational Procedures for Compliance with the COA

A number of operational procedures must be met in order to perform the flight safely and comply with the COA. The OSU nationwide COA states that "sterile cockpit" and "see-and-avoid" procedures must be met. To ensure a sterile cockpit, the project team will require the audience (if any) to stay at least 20 ft. from the crewmembers in order to eliminate distractions. For a sterile cockpit, the following COA requirements must be met:

- No crewmember may perform any duties during a "critical phase of flight" not required for the safe operation of the aircraft. A critical phase of flight includes all ground operations involving taxi, take-off and landing, and all other flight operations in which safety or mission accomplishment might be compromised by distractions.

- No crewmember may engage in, nor may any PIC permit, any activity during a critical phase of flight which could distract any crewmember from the performance of his/her duties, or interfere in any way with the proper conduct of those duties.

- The pilot and/or the PIC must not engage in any activity not directly related to the operation of the aircraft.

- The use of cell phones or other electronic devices is restricted to communications pertinent to the operational control of the unmanned aircraft and any required communications with Air Traffic Control.

- The PIC or the VO are required to maintain VLOS of the aircraft and meet the required see-and-avoid procedures stated in the COA. The PIC is responsible to remain clear and give way to all manned aviation operations and activities at all times, ensure the safety of persons or property on the surface, and ensure that there is a safe operating distance between aviation activities and unmanned aircraft at all times.

- The PIC is responsible to ensure that any VO can perform their required duties, are able to see the aircraft and the surrounding airspace throughout the entire flight, and are able to provide the PIC with the aircraft's flight path and proximity to all aviation activities and other hazards (e.g., terrain, weather, structures).

- Unlike Part 107 rules, at least one VO must be used at all times and must maintain instantaneous communication with the PIC. Electronic messaging or texting is not permitted during flight operations. The use of multiple successive VOs (daisy chaining) is also prohibited.

3.2.6.2 Emergency Procedures for Compliance with the COA

In addition to the operational procedures in the previous section of this report, the COA also includes a number of provisions regarding procedures in the event of an emergency. These provisions, as well as techniques to meet them, are listed below.

- If the aircraft loses link or communications with its GCS, then the COA requires the aircraft to initiate a flight maneuver that ensures safe and timely landing. Such a maneuver is named "lost link" procedures in the COA. For the sUAS tested in this study, they were programmed to return to their home point in the event or losing link with the GCS. If for some reason this does not work, then the OSU team will next send a "return-to-home" signal using the GCS. If that does not work, then the final step is for the PIC to initiate a secondary flight controller to override the GCS and land the aircraft as quickly and safely as possible.

- As shown in Figure 3.10, a virtual donut or fence will be placed around the defined operating area. If the aircraft reaches the inner boundary of the donut, the GCS will send a "return-to-home" signal. If this does not work, then the PIC will use the secondary flight controller. If the aircraft still somehow leaves the defined operating area, then the COA requires that the PIC notifies Air Traffic Control immediately to advise them of the last known altitude, speed, direction of flight and estimated flight time remaining for the aircraft.

- The COA requires the VO to notify the PIC immediately if he/she loses sight of the aircraft. If the aircraft is then visually seen promptly, then the mission may continue. If not, the PIC will execute the lost link procedures. The PIC will also execute the lost link procedures if the PIC loses communication with a VO.

3.2.6.3 Manual Flights

The next three subsections of this report discuss different methods for performing the flights and acquiring the data. Any of the flights discussed in these sections must meet the aforementioned COA provisions for operational and emergency procedures.

The first method discussed in this report is “manual” mode. In this mode, the pilot uses a remote controller for sending thrust, roll, pitch, and yaw signals to the aircraft without assistance from other sensors, such as GPS or ultrasonic. Because of the lack of sensor assistance, this mode is less safe and is generally not recommended for performing inspections. For this study, it was only used in emergencies for recovering the aircraft when it lost link with the GCS.

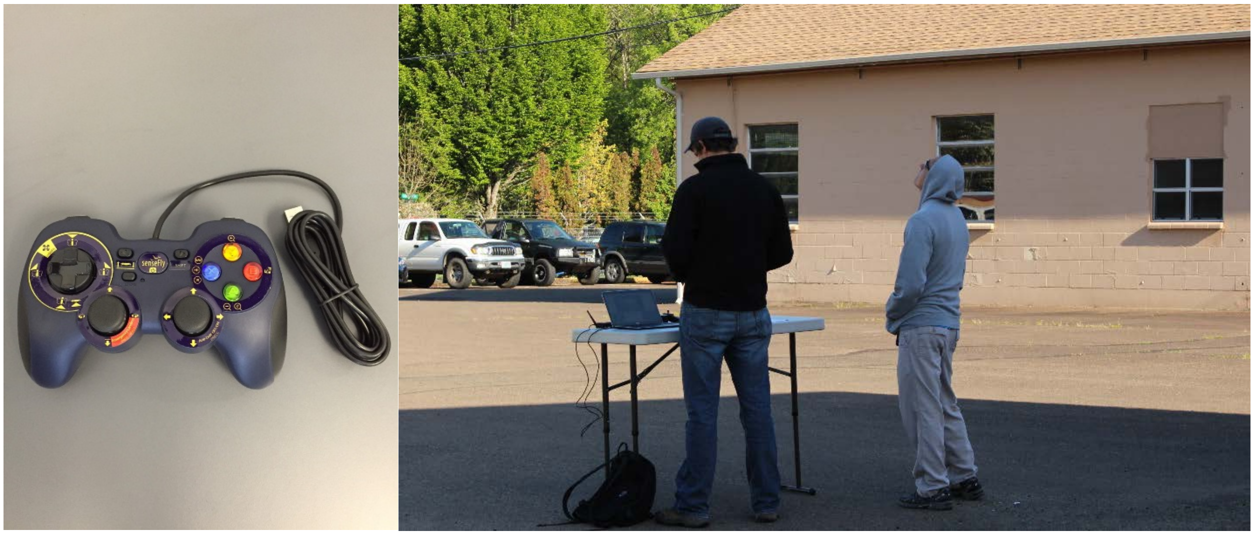
3.2.6.4 Sensor-Assisted Manual Flights

The next flight method in this report is named “sensor-assisted manual” mode. This mode is still considered a “manual” mode because the pilot still uses a flight controller for sending thrust, roll, yaw, and pitch signals to the aircraft. However, this mode also takes advantage of on-board GPS and/or ultrasonic sensors for assisting with the flight.

GPS-assisted manual flight is a common flight mode among outdoor UAS operators. GPS enables a multicopter to stop and hover when the operator stops applying thrust to the aircraft. This is particularly helpful during inspection, because the multicopter can hover in place while collecting imagery of a particular feature. GPS simplifies flying and helps the pilot carefully position a multicopter in an advantageous location for acquiring data. Without GPS, the aircraft will tend to drift or wander off of a position, especially if the site is windy. Unfortunately, the inspections often required an aircraft to fly very close and even underneath a feature of interest (e.g., beneath a bridge) in order to capture highly resolute images. Flying close to or underneath structures results in blocked or degraded GPS signals. When using GPS-assistance during flight, if the GPS signal degrades below a particular threshold, the GCS can be set to attempt to return the aircraft to its home point. This setting was disabled to prevent the aircraft from attempting to automatically fly back to its home point (and possibly crash into an obstacle) when flying beneath the bridge.

Some aircraft, like the albris used in this study, are equipped with ultrasonic sensors for assisting flights. The ultrasonic sensors are useful for detecting and warning the pilot of obstacles. If an obstacle was within a specified distance of the albris, the GCS begins beeping and warning the pilot. In addition, the pilot could use one of the ultrasonic sensors to “hold” the aircraft at a specified distance from an obstacle. For instance, the sensor was used to hold the albris three meters from a wall or above/beneath a bridge deck during flights.

During sensor-assisted manual flights, the pilot uses the controller (Figure 3.13a) to trigger the camera. All of the aircraft in this study are also capable of broadcasting live video from its camera(s) to a monitor in front of the operator (Figure 3.13b). The first-person view video provides enhanced perspective of the position of the aircraft, and it helps the operator ensure that imagery is captured of desirable features on the structure.



(a) (b)

Figure 3.13: (a) A radio controller for operating the UAS in "sensor-assisted" manual mode; (b) photo of pilot controlling the aircraft in this mode while viewing the first-person-view monitor, and a visual observer watching the aircraft during flight

3.2.6.5 Waypoint-Assisted Flights

Sensor-assisted manual missions require significant human interaction. For less human interaction, waypoint-assisted missions can be programmed using mission planning software. Waypoint missions are useful for systematically capturing imagery along a well-defined path. Figure 3.14 shows a variety of waypoint missions for mapping a site or for flying about a tall, thin structure such as a tower. When programming a flight, the planner can specify the desired amount of photo overlap and how or where to point and trigger the camera. After uploading the flight plan, the aircraft stores the mission on its on-board computer. Using the GCS, the pilot next issues a command for the unmanned aircraft to take-off, and then using GPS as well as inertial sensors, including accelerometers and gyroscopes, the aircraft will fly the programmed mission. The aircraft can be set to trigger the camera at the locations specified in the mission plan.

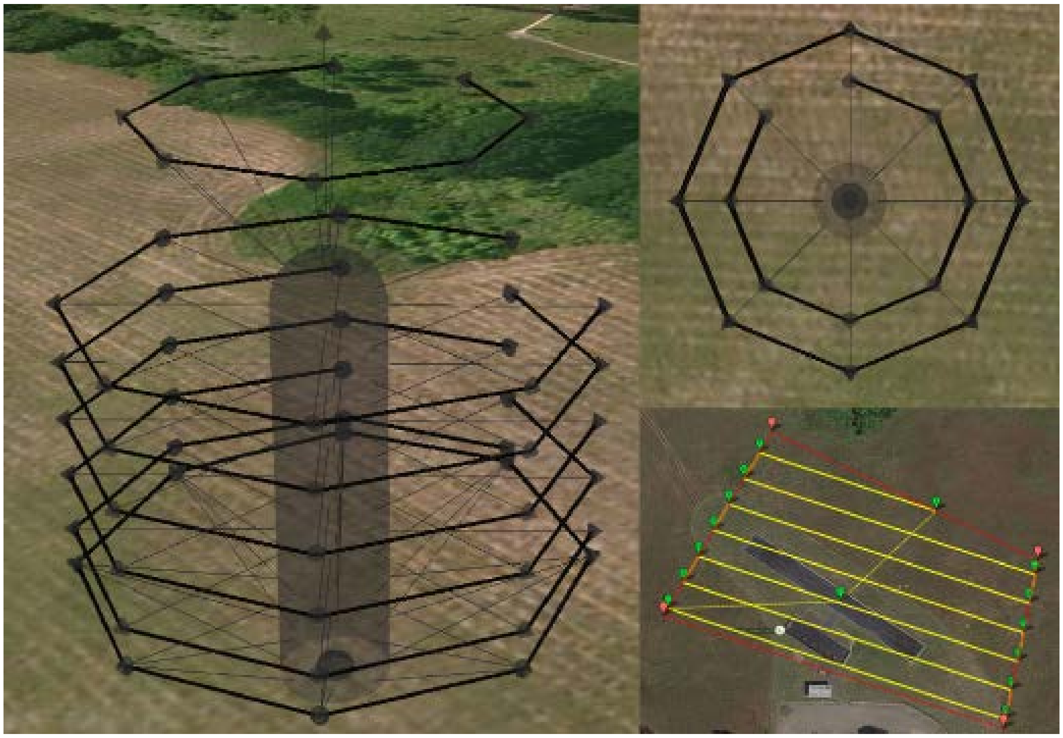


Figure 3.14: Waypoint missions – Left- 3D view of a cylinder flight plan. Top right- plan view of cylinder flight plan. Bottom right- plan view of horizontal mapping flight plan

Because imagery is collected in a systematic manner, this flight mode is especially beneficial for reconstructing 3D models from the overlapping imagery. By post-processing overlapping images using SfM and photogrammetric techniques, it is possible to align and orthorectify the photos to produce a 3D point cloud, digital surface model, and orthophoto of the site. Using ground control points, these models can also be output in a known coordinate system. These post-processing techniques generally require at least 80% overlap between photos, which can be readily achieved using waypoint-assisted flight plans.

Table 3.3 summarizes some of the key advantages of sensor-assisted manual and waypoint-assisted flights. Although the report breaks these types into two categories, it is important to understand that both types of flights have advantages and both can be performed during the inspection of a structure.

Table 3.3: Comparison of the advantages of flight methods for acquiring data

Sensor-Assisted Manual Missions	Waypoint-Assisted Missions
Advantages Operator can carefully position the camera to view a specific feature of interest Close-up photos Less time	Advantages Overlapping photos can be developed into a 3D model Systematic flights assure features are photographed Less human interaction required

3.2.7 Post-Processing

Post-processing is the final phase after all flights have been conducted and data collected. The acquired data was downloaded and backed up after completion of the flights.

For some structures, development of a 3D model of the structure was another objective of the UAS mission. In this case, the acquired imagery was post-processed using SfM software (e.g, *Agisoft Photoscan, Pix4D Mapper*, etc.). SfM is a computer vision and photogrammetric range imaging technique for developing 3D point clouds of features from 2D overlapping images. It is a relatively new technique that is gaining widespread use for generating high-resolution point clouds and orthomosaics from UAS imagery acquired with inexpensive, consumer-grade cameras with sufficient endlap and sidelap (i.e., ~80%).

During SfM processing, correspondence or “key features” between overlapping images (i.e., edges with gradients or changes in contrast in multiple directions) are automatically identified using a detector technique. With sufficient correspondence and without human interaction, it is possible to solve for the intrinsic parameters, orientation, and 3D position of the camera when the image was captured by a highly redundant, iterative bundle block adjustment. Using multi-view stereopsis techniques, a so-called “dense” point cloud is then derived in the oriented block from the bundle adjustment. The resulting point cloud is highly resolute and similar to lidar-derived point clouds. Orthophotos and digital elevation models can be derived as secondary products from SfM point clouds.

However, the SfM algorithms will output results in an arbitrary coordinate system unless given additional information. For this project, ground control points were established by surveying a set of aerial targets. The coordinates derived from this survey were inserted in the software for these points, and the aerial targets were identified in each image. The software then transformed the 3D point cloud from an arbitrary coordinate system to the georeferenced coordinate system of the survey. Another option is to use equipment capable of directly georeferencing the imagery collected on the UAS. However, such direct georeferencing equipment is quite expensive, rarely used on sUAS because of its weight and cost, and was not available for use in this project.

A point cloud can be used to measure and define the geometry of the structure. Since it is georeferenced, it can also be readily input in a geographic information system. Another benefit is that the 3D model can also function as a “digital database” for organizing and storing the photos, and for documenting where each photo was taken. Chapter 4 shows resulting UAS and SfM-derived point clouds of a bridge and tower inspected as part of this study. It also discusses the benefits of such point clouds and how they can be used as a digital database for managing and organizing the large volume of images that are collected during a UAS inspection.

4.0 IMPLEMENTATION: UAS TEST INSPECTIONS

The methodology and equipment discussed in the previous chapter were used to complete several test inspections of five bridge sites (note one bridge was done twice) and three wireless communication tower sites. An additional tower inspection was attempted at a fourth site, but it was not completed, due to interference from nearby wireless internet service provider (WISP) towers. All flights were conducted under an FAA COA (2014-WSA-212-COA for the Independence Bridge flights, and 2016-WSA-101-COA for all flights after May 11, 2016, when this COA was signed).

This section of the report presents examples of some of the imagery collected from the UAS at the sites. Items of specific interest for communication tower (CT) and bridge (B) inspections include:

- Connections – investigate the condition of bolts, rivets, etc. for defects. (CT,B)
- Banks – view conditions upstream and downstream of the bridge identifying any erosion or scouring. (B)
- Bearings – evaluate alignment for possible movement, bulging, tearing, etc. (B)
- Guy Wires and associated hardware – Ensure there is no splitting or fraying in the cables and that they are securely attached, see connections. (CT)
- Joints – look for leakage, concrete spalling, steel section loss, cracking, etc. (B)
- Ladders/Safety Devices – ensure the connections/members of the safety devices are adequate prior to allowing an inspector to use those devices. (CT,B)
- Paint/Galvanization health – assess rust stains, crevice and pack rust, paint clouding, prior paint patching, etc. (CT,B)
- Damage that could degrade the integrity of structural members, e.g., bullet holes. (CT,B)

This chapter provides a summary and discussion of the results of each of the test inspections summarized in Tables 4.1 and 4.2, and shown in Figure 4.1. Note that all of digital data collected during these test inspections, including the raw imagery, video, and resulting point clouds and orthophotos were submitted to ODOT on an external hard drive as an attachment to this report.

Table 4.1: Summary of Bridge Inspection UAS Flight Missions Conducted to Date by OSU Project Team

Bridge ID	Bridge Inspection	Bridge Number	Acquisition Date(s)	Unmanned Aircraft Used	Number of High-Res, RGB Still Photos Acquired
B1	Independence	05789A	Sept 21, 2015	DJI Phantom 3 Pro	342
B2	Crooked River	00600	July 13, 2016	senseFly albris	401
B3	Mill Creek	01600	July 14, 2016	senseFly albris	197
B4	St Johns	06497	Sept 24, 2016	senseFly albris and DJI S900 w/ Sony wx500	226 (91 with albris and 135 with S900)
B5	Winchester	07663C	March 22, 2017	senseFly albris	363
B6	St Johns (Detailed Inspection)	06497	April 17-21, 2017	senseFly albris and DJI S900 w/ Sony wx500	2536

Note: The Independence Bridge was not specifically flown as part of this project, but, rather, as part of an earlier PacTrans project (Grant DTRT12-G-UTC10) conducted by the research team (see Gillins et al. 2016b). It should also be noted that the numbers of images listed do not include thermal images, wide-angle navigation camera (navcam) images or video. Hence, the total number of images acquired for each project is actually much higher than listed here.

Table 4.2: Tower Inspection UAS Flight Missions Conducted to Date by the OSU Project Team

Tower ID	Tower Inspection	Acquisition Date(s)	Unmanned Aircraft Used	Number of High-Res, RGB Still Photos Acquired
T1	Woodburn tower (Not ODOT tower; managed by Marion County)	April 22, 2016	senseFly albris and ATI/DJI S900	163 (124 with albris and 39 with S900)
T2	Corvallis Maintenance Tower	April 25, 2016	senseFly albris	161
T3	Washburn Butte tower	April 25, 2016	senseFly albris	564
T4	Grizzly Mountain tower	July 15, 2016	senseFly albris, S900	0

Note: The Grizzly Mountain tower was attempted, but not completed, due to interference from nearby WISP towers which prevented communication between the GCS and unmanned aircraft.

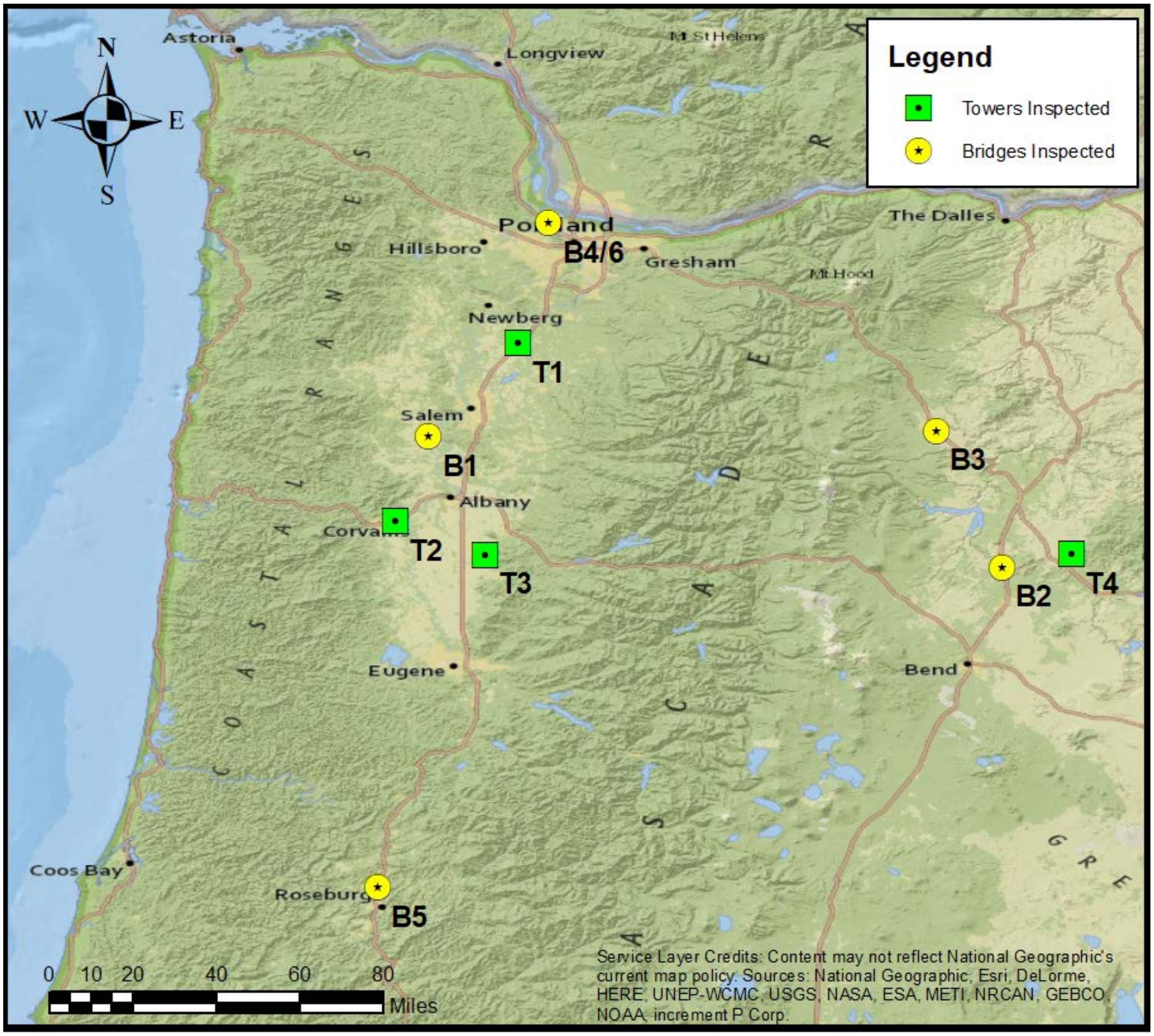


Figure 4.1: Overview map of all bridges and towers inspected as described in tables 4.1 and 4.2

4.1 TEST BRIDGE INSPECTIONS

4.1.1 Independence Bridge

UAS flights were conducted along the Independence Bridge, a deck-plate girder bridge over the Willamette River on River Road South, Marion County, Oregon (Figure 4.2). 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 4.2: Independence Bridge over the Willamette River, Oregon

A DJI Phantom 3 Pro multicopter equipped with a gimballed camera capable of collecting ultra-high-definition 4k video and 12 megapixel photography was used for the tests (Figure 3.1). 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, numerous other systems are available on the market and some may be better suited for performing structural inspections.

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 3.1). While hovering close to the girders, the pilot rotated the pitch up and down on the gimballed camera and captured the 4K (ultra-high definition) video. The aircraft was then slowly flown parallel to the girder, 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.

The UAS successfully collected 55 minutes of 4K video of both the upstream and downstream sides of the bridge superstructure and substructure. 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 4.3 to 4.9) 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. Cropping still imagery from the video and pasting it in this report is useful for showing some examples of UAS capabilities; however, it is important to underscore that resolution is lost when extracting still imagery from 4K video and pasting it in a report document. Interested readers will see much greater detail of the bridge by viewing the 4K video on a device capable of playing and displaying ultra-high definition video. Some discussion of the results of this experiment are also given in Gillins et al. (2016a, 2016b).

Figure 4.3 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 4.4 presents some of the bolts and bolt patterns at the joints of steel members which could be analyzed for possible rust. Some cracking of a concrete guard rail is evident as per Figure 4.5. Figure 4.6 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. Figure 4.7 depicts an important connection between two of the steel girders on the bridge. Efflorescence was evident on many of the concrete towers directly beneath the steel beams (e.g., Figure 4.8).

In addition to collecting video of the bridge, the aircraft was also flown along the banks of the river on both the upstream and downstream side 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 approximately a speed of 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 4.3: Evidence of a leaking joint. (Cropped image)

Figure 4.4: Example imagery of bolt patterns at steel connections. (Cropped images)

Figure 4.5: Cracking of concrete railing. (Cropped image)

Figure 4.6: Connection of steel member to concrete tower; note the missing bolt nut. (Cropped image)

Figure 4.7: Connection of two steel girders. (Cropped image)

Figure 4.8: Efflorescence on concrete columns. (Cropped images)

Figure 4.9: Bank of river upstream of bridge. (Cropped image)

4.1.2 Crooked River Bridge

UAS flights were conducted along the Crooked River (High) Bridge, a bridge located 5 km north of Terrebonne, Oregon, which crosses over the Crooked River Gorge next to US Highway 97 in the Peter Skene Ogden State Park. It is a steel arch bridge completed in 1926, having a total length of 141 m and a main span of 100 m (Figure 4.10). It is situated 90 m above the base of a gorge with near-vertical walls. Due to the increased traffic on US 97, a newer and wider bridge known as the Rex T. Barber Veterans Memorial Bridge was completed in 2000 to replace the

Crooked River Bridge on the highway. Today, the Crooked River Bridge is only used by pedestrians.

Figure 4.10: Crooked River Bridge located north of Terrebonne, Oregon, at Peter Skene Ogden State Park

The objective of this mission was to target specific areas difficult to inspect using traditional methods, such as the lower abutment connections to the canyon wall, as well as obtaining full coverage of all other key bridge features (i.e. bearing pads, rivet plates, member and deck health, etc.). In addition to the imagery, the project team also wanted to collect overlapping images in order to create a 3D point cloud of the bridge using SfM software.

To begin this test, several GCPs consisting of 1-meter square black and white targets and easily identifiable features of the bridge (i.e., concrete joints in the bridge deck) were surveyed using a total station and dual frequency GNSS receiver utilizing Oregon's Real Time GNSS Network (ORGN). Once a control survey of the site was completed, an overhead waypoint-assisted rectangular flight was conducted in order to collect overlapping, nadir, imagery of the bridge deck. The overhead flight plan can be seen in Figure 4.11 below. When creating the waypoint mission in the Emotion 3 flight control software the user selects the AOI, inputs the desired ground sampling distance (resolution), and overlap and side-lap percentages. The software then optimizes the flying height to meet the specified user inputs while minimizing the number of photos.

Figure 4.11: Rectangular overhead flight plan for capturing nadir imagery over the crooked river bridge. This flight plan was created in emotion 3 where each circle along the flight line is waypoint at which the camera was triggered

The mission plan was uploaded to the senseFly albris, and overhead flights with this aircraft were completed. Afterwards, manual flights with sensor assistance were completed with the albris. Due to the narrowness and spacing of the bridge members, the ultrasonic sensors were not able to hold the aircraft at a fixed standoff distance from the bridge. To counter this issue, the pilot used the onboard navcams to slowly position the aircraft within approximately 3 to 5 m of the top of the trusses. Once the aircraft was set to the appropriate distance, the pilot then used a senseFly tool on the radio controller known as "cruise-control." Using cruise-control, the aircraft will slowly fly left or right, as specified by the pilot, with the camera pointed at the bridge like shown in the schematic in Figure 4.12. The pilot then triggered the camera using the radio controller while the aircraft was slowly moving left or right. In addition to the imagery collected using the waypoint-assisted and sensor-assisted manual flights utilizing cruise left/right capabilities, close-up imagery was collected by hovering the aircraft near areas of specific interest using first-person view video and by rotating the gimbal for the camera up and down.

Some examples of imagery collected with the albris from manual flights with sensor-assistance and using the cruise control tool are given in Figures 4.13 through 4.19.

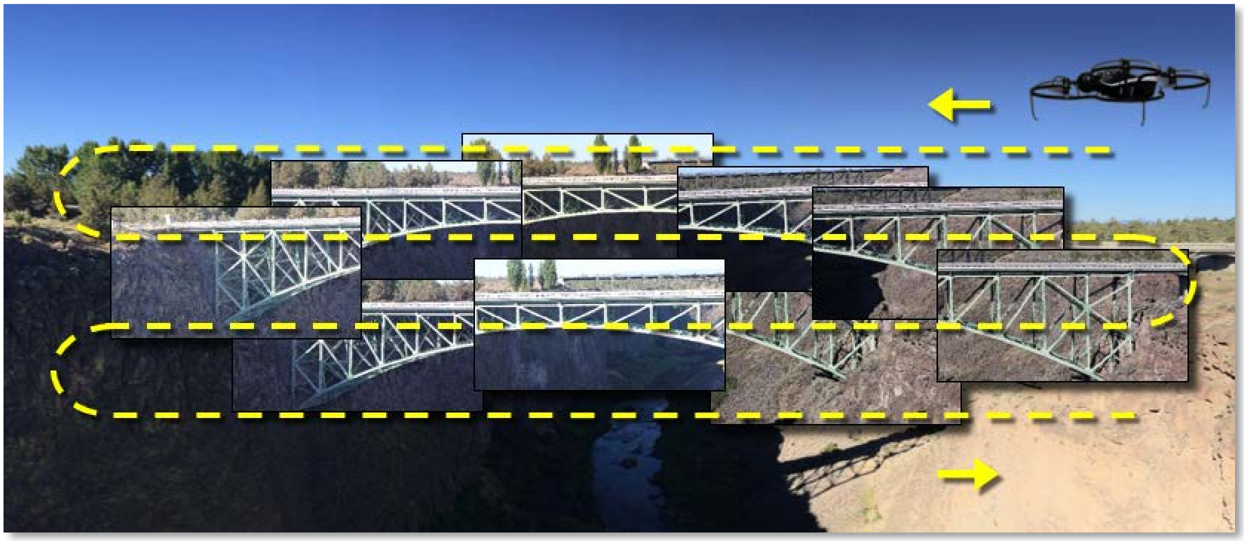


Figure 4.12: Schematic representation of overlapping images taken from a UAS and the flight path using manual flight mode with sensor assistance (from Javadnejad et al. 2017, with permission)

Figure 4.13: Intricate member connection on bridge. (Cropped image)

Figure 4.14: Crooked River Bridge bearing connection. (Cropped image)

Figure 4.15: Deck bearing girder connection on Crooked River Bridge. Note the small crack in the deck at the location of support and recent paint patchwork in darker green. (Cropped image)

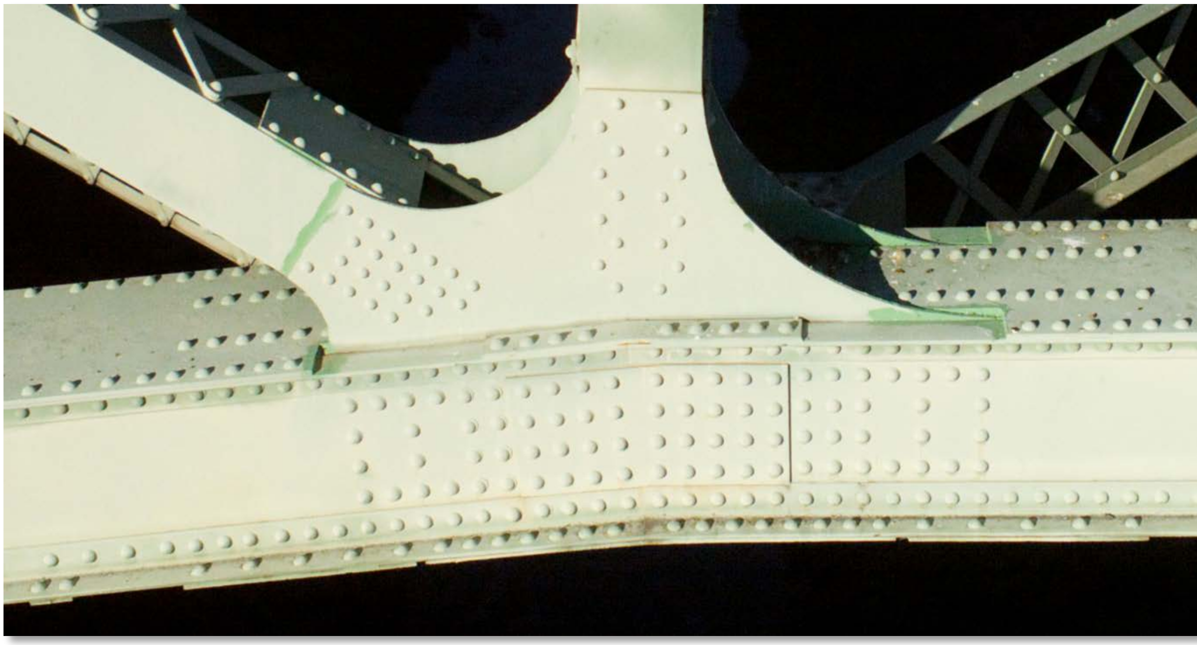


Figure 4.16: One of the lower chord gusset plates on the Crooked River Bridge. (Cropped image)

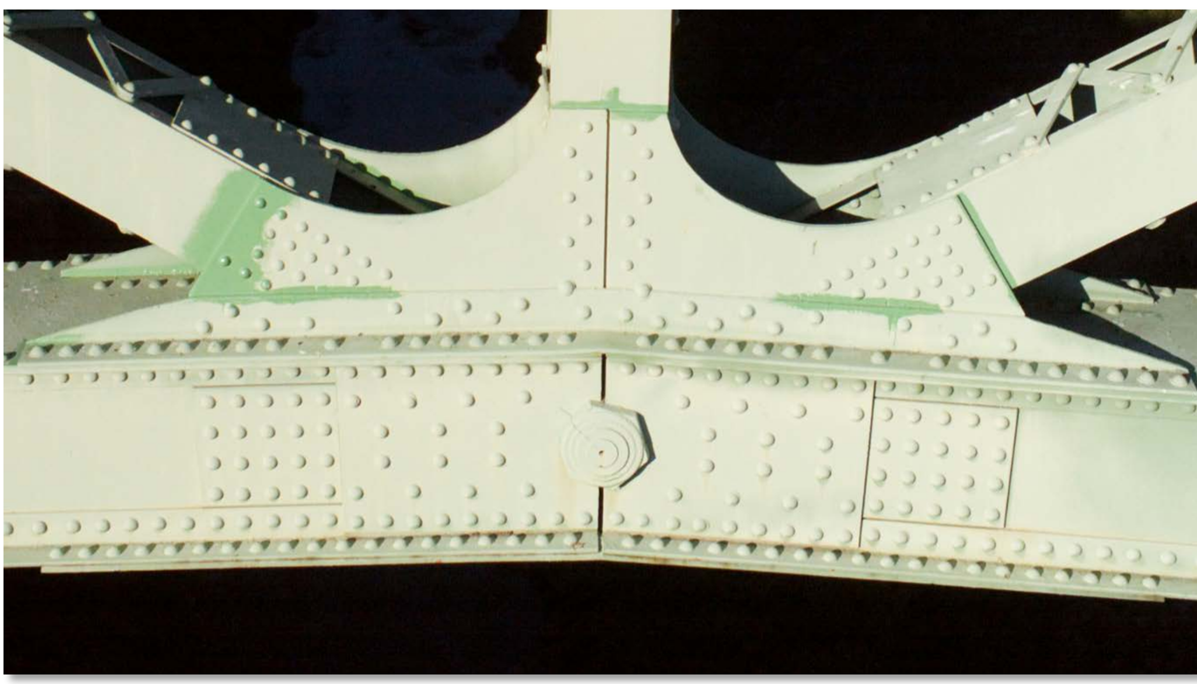


Figure 4.17: Mid-span pin connection for lower chord on the arch of the Crooked River Bridge. (Cropped image)

Figure 4.18: Rolling pin on northeast corner of the Crooked River Bridge. (Cropped image)

Figure 4.19: Lower abutment connection on northwest corner of bridge - into the wall of the gorge. Note the shadow at this location (Cropped image)

After the flights, the images were post-processed in SfM software (i.e., Agisoft Photoscan), producing a 3D point cloud of the bridge (Figures 4.20-4.21). The coordinates derived for the survey at each of the GCPs were uploaded, and these points were identified in the imagery. The northings and eastings of the final point cloud were output in the 1983 Oregon North Zone State Plane Coordinate System (NAD 83(2011) Epoch 2010.00), and the orthometric heights (i.e., elevations) of the final point cloud were output relative to the North American Vertical Datum of 1988.

The point cloud can be used to estimate the geometry and size of members on the bridge. In addition, the point cloud can be used to ortho-rectify the imagery collected from the UAS. Combining the ortho-rectified imagery aligned by SfM techniques, an orthophoto of a profile view of the bridge was produced as shown in Figure 4.22.

Figure 4.20: 3D point cloud of the Crooked River Bridge created from overlapping 2D imagery

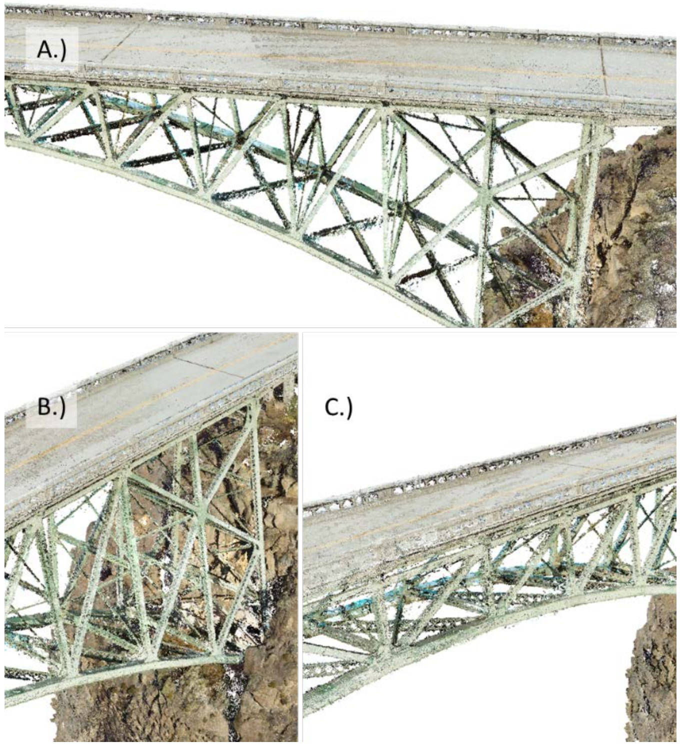


Figure 4.21: Various, detailed views of Crooked River Bridge point cloud

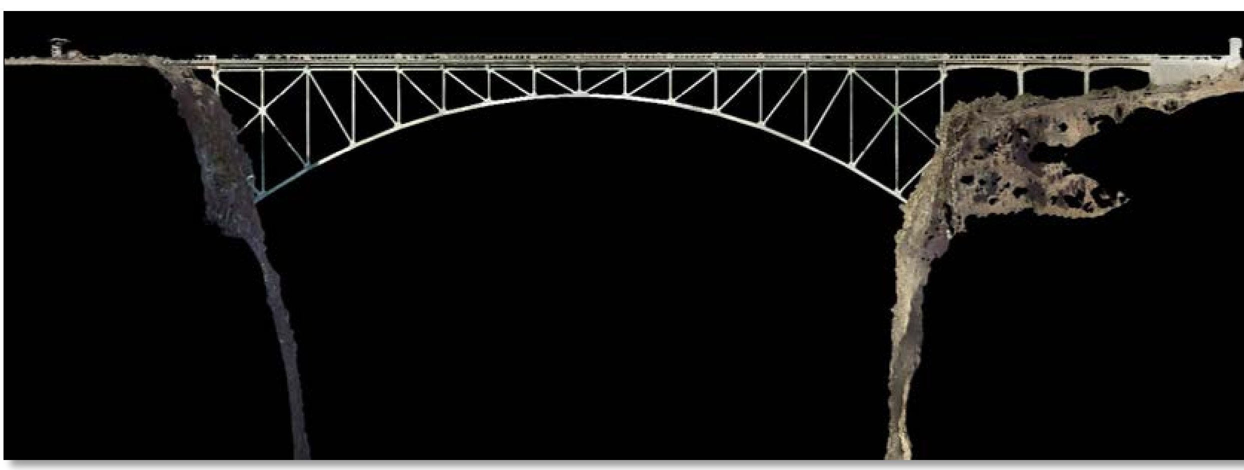


Figure 4.22: An orthophoto of the profile of the Crooked River Bridge produced from processing the images using SfM. (from Javadnejad et al. 2017, with permission)

4.1.3 Mill Creek Bridge

Test UAS inspections with the senseFly albris were also conducted for the Mill Creek Bridge, located 11 miles northwest of Warm Springs, Oregon. This bridge crosses over Mill Creek on US Highway 26. It is a Cantilevered Warren deck truss bridge having a total length of 163 m and a main span of 50 m (Figure 4.23). It is situated 68 m above the gorge base and was completed in 1948.

Figure 4.23: Mill Creek Bridge on US 26 in Wasco County, Oregon

Similarly to the Crooked River Bridge, the objective of this mission was to target specific areas that are difficult to inspect using traditional methods, such as the lower abutment connections, as well as obtaining full coverage of all other key bridge features (i.e. bearing pads, rivet plates, member and deck health, etc.). In order to meet COA provisions, the aircraft was limited to a flying height beneath the side barriers along the deck of the bridge, and no overhead flights were conducted. Similar to the Crooked River Bridge, manual flights with sensor assistance, utilizing the cruise left/right capabilities of the aircraft, were primarily used. The pilot positioned the aircraft approximately 3 to 5 m from the bottom chord of the bridge truss using the navcams. Once the aircraft was set to the standoff distance, the PIC used the cruise control left/right tool to collect the imagery along the bridge span. Rotating the gimbal holding the front-mounted camera up and down, imagery was also collected upward and downward at areas of specific interest, such as of the tops of the pedestals and along the two towers.

Some of the imagery collected at the Mill Creek Bridge are shown below, resulting from manual flights with sensor-assistance and using the cruise control tool. Again, the original, high-definition images of the bridge show greater detail than the images pasted in this report.

Figure 4.24: Mid span connection pin at upper chord of Mill Creek Bridge. Note that lettering written by inspectors during previous inspections are legible in the image. (Cropped image)

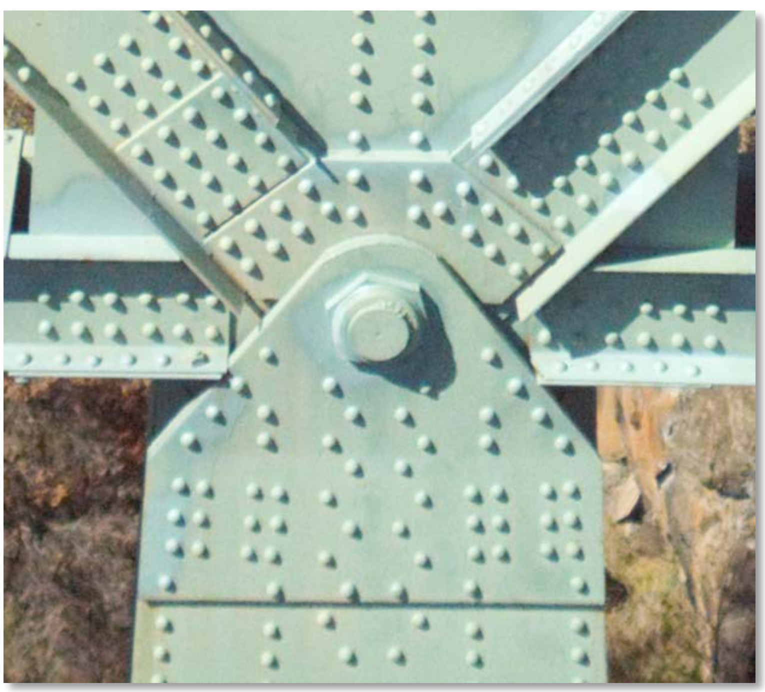


Figure 4.25: Pin connecting the bridge span to one of the tower supports. (Cropped image)

Figure 4.26: Northern support tower of the bridge with large areas of rust and peeled paint on members and gusset plates. (Cropped image)

Figure 4.27: One of the lower chord connection plates on the bridge. Note the rust around the connection pin. (Cropped image)

4.1.4 St. John's Bridge (09/2016 preliminary test)

A UAS inspection of St. Johns Bridge (Bridge 06497), southwest of St. Johns, Oregon, was completed on September 24, 2016. It was constructed in 1931 and rehabilitated in 2005, having a total length of 1100 m and a main span of 368 m (Figure 4.28). The bridge's main spans are classified as a wire cable suspension with the approaching spans being classified as metal rivet-connected warren deck truss. In order to meet COA provisions, the aircraft was limited to a flying height below the side barriers along the deck of the bridge, and no overhead flights were conducted.

Figure 4.28: St. Johns Bridge located southwest of St. Johns, Oregon at Cathedral Park

This test inspection primarily focused on testing the use of an optical zooming camera to acquire detailed imagery from a safer stand-off distance (>5 meters). The main benefits to flying at a larger standoff distance is the increased safety by reducing the likelihood of crashing (e.g., due to sudden wind gusts and/or reduced depth perception when operating close to a bridge); however, it does reduce the effectiveness of using a headlamp in poorly illuminated areas. To perform these flights, the research team equipped a 30x optical zoom digital camera (i.e. Sony WX 500) onto a 3-axis gimbal on the aforementioned custom DJI S900 hexacopter.

All of the flights were completed in manual mode with sensor assistance. During each flight, the pilot would allow the aircraft to hover roughly ten meters from the bridge. Then, using the controller, the pilot looked at the first-person view monitor and pointed the onboard gimballed camera at a feature of interest and increased the optical zoom level of the camera until high-resolution imagery could be obtained. Due to the configuration of the gimbal, the camera frame was positioned using both the gimbal (roll and pitch) and by sending yaw signals to the unmanned aircraft.

In addition to collecting imagery with the optical zoom camera on the DJI S900, the senseFly albris was also flown to collect imagery of the bridge. Similar to the Crooked River Bridge (section 4.1.2), manual flights with sensor assistance, utilizing the cruise left/right capabilities of the aircraft, were primarily used. The pilot positioned the aircraft approximately 3 to 5 m from a desired bridge member using first-person view and ultrasonic sensors. Once the aircraft was set to the standoff distance, the PIC used the cruise control left/right tool to collect the imagery along the bridge span and supporting columns. Rotating the gimbal holding the front-mounted camera up and down, imagery was also collected at areas of specific interest, such as of the tops of the pedestals, and along the columns and spans.

Some of the imagery collected at the St. Johns Bridge are shown below, resulting from two different methods: piloting a custom DJI S900 equipped with an optical zoom camera; and manual flights with sensor-assistance and using the cruise control tool equipped on the senseFly albris. The figure captions identify which method was used to derive the associated image.

Figure 4.29: Photo of northeast connection on span 6. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 85 mm, 35mm; equivalent: 500 mm

Figure 4.30: Northwest side of east tower (bent 6). Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 123 mm, 35mm equivalent: 700 mm

Figure 4.31: Bearing pad connection on the top north side of Bent 7. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 26 mm, 35mm equivalent: 154 mm

Figure 4.32: Gusset plate connection on north east side of span 6. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 28 mm, 35mm equivalent: 163 mm. (Full image)

Figure 4.33: Bearing pad connection on the top north side of Bent 7. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 4 mm, 35mm equivalent: 24 mm. (Full image)

Figure 4.34: Top north side of Bent 7. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 7 mm, 35mm equivalent: 40 mm. (Full image)

Figure 4.35: Bearing pad connection on the top north side of Bent 7. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 24 mm, 35mm equivalent: 139 mm. (Full image)

Figure 4.36: Large bolt on the northeast side of span 6. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 24 mm, 35mm equivalent: 139 mm. (Full image)

Figure 4.37: Large bolt on the northeast side of span 6. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 54 mm, 35mm equivalent: 316 mm. (Full image)

Figure 4.38: Vegetation growing on northeast side of span 6. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 54 mm, 35mm equivalent: 316 mm. (Full image)

Figure 4.39: Large bolt connection for lower cord of spans 5 (right) and 6 (left) on North side of east tower. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 21 mm, 35mm equivalent: 123 mm. (Full image)

Figure 4.40: Gusset plate connection on the west side of the lower cord of spans 6. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 30 mm, 35mm equivalent: 178 mm. (Full image)

Figure 4.41: Connection for span 6 (left) to North side of east tower. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 13 mm, 35mm equivalent: 75 mm. (Full image)

Figure 4.42: Large bolt connection for lower cord of spans 6 left on North side of east tower. Taken from S900 equipped with a Sony DSC-WX500 optical zoom digital camera. Focal length: 19 mm, 35mm equivalent: 112 mm. (Full image)

Figure 4.43: North side of the East tower footing. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.44: South side of the East tower footing. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.45: Moss growing on east tower footing. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.46: Moss growing on east tower footing. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.47: North side of the East tower footing. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.48: Significant spalling with exposed metal on bent 7. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

4.1.5 Winchester Bridge

A test UAS inspection of the Winchester Bridge (Bridge 07663C), north of Roseburg, Oregon, was completed on March 22, 2017. The UAS flights were coordinated to coincide with the actual ODOT inspection of the bridge in order to get real-time input from the inspectors.

Figure 4.49: Winchester Bridge on I-5 South North of Roseburg, Oregon

In total, the project team conducted four flights and captured a large amount of imagery of the west face of the southbound bridge (Bridge 07663C). All four flights were completed in manual mode with sensor assistance using the senseFly albris.

For two of the flights, the cruise left/right capabilities at 0.5 m/s with a firing rate of 6 seconds were tested. The aircraft was flown parallel with the bottom bridge girder at a standoff distance of 3 to 5 meters. The other two flights were completed where the aircraft was flown to specific locations to obtain more detailed images of various members/connections (stand-off distance of 3.5-4.5 meters). During the manual flights, ODOT bridge inspector Erick Cain stood by at the GCS to view the real-time video feed and indicate what he saw and where the flight crew should focus its efforts. No major problems were encountered in these inspections. Poor weather initially appeared to be a problem for the flights; however, the rain stopped long enough for the project team to complete the UAS flights. Some spontaneous wind gusts pushing the aircraft toward the structure were encountered, requiring a slightly increased stand-off distance.

Some of the imagery collected at the Winchester Bridge are shown below, resulting from manual flights with sensor-assistance and using the cruise control tool equipped on the senseFly albris.

Figure 4.50: Southern bent pin connection. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.51: Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.52: Spalling with exposed rebar in deck soffit. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Cropped image)

Figure 4.53: Southern bent pin connection. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.54: Southern bent pin connection. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.55: Spalling with exposed rebar in deck soffit. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

4.1.6 St. John's Bridge (02/2017 detailed test)

A more thorough inspection of St. Johns Bridge (Bridge 06497), southwest of St. Johns, Oregon, was completed throughout the week of April 17th, 2017. The purpose of this week-long effort was to focus on testing all of the previously identified challenges from the prior tests and provide the most thorough data set as possible for evaluating UAS for inspecting bridges. Thus, this test is considered the most "detailed" test conducted as part of this study.

Figure 4.56: St. Johns Bridge located southwest of St. Johns, Oregon at Cathedral Park

For the majority of the flights, Erick Cain, ODOT's Bridge Inventory Coordinator, stood near the GCS to provide real-time feedback on the data being acquired. ODOT Project Coordinator, Joe Li, also attended the final flights. In total, 28 flights were completed capturing thousands of photos using the senseFly albris. Due to nesting peregrine falcons on the west end of the St Johns Bridge and COA constraints, the test flights were limited to the eastern half of the bridge (approximately 550 meters east from the center of the main span).

The flight patterns used to collect data along the bridge varied based on the sections of the bridge being inspected, but the majority of flights were similarly flown in manual mode with sensor assistance utilizing the cruise left/right/forward/backward capabilities. When imaging long horizontal stretches, such as the girders along the spans and underneath the bridge deck, the aircraft was positioned such that the following criteria were achieved: maintained a stand-off distance less than 5 meters; adequate lighting; proper visualization of key members/connections; and no obstructions or objects in flight path. If the mentioned criteria could not be satisfied the aircraft was relocated until all were met. Once the proper position was found the pilot utilized the cruise capabilities at a flying speed of 0.3-0.5 m/s with an image firing rate of 6 seconds. The image firing rate selected was the fastest firing rate allowed by the flight control software. As the aircraft cruised along, its position was continuously adjusted to maintain the mentioned criteria. For more detailed inspection of specific members and connections, the aircraft was also flown to a specific hovering location to manually capture detailed imagery at a stand-off distance of 3 to 5 m. The mentioned criteria was also used when inspecting the columns, with the exception being that the cruise capabilities were not used. Instead, the throttle was increased/decreased in order to fly the aircraft up and down the columns while the pilot manually or automatically triggered the camera.

It is important to note that this was also the first bridge where test flights were conducted directly beneath the bridge deck. During these flights, the aircraft was flown directly underneath the deck roughly 5 m below the lowest bridge members with the camera pointed straight upward. During all previous tests, such a flight was avoided due to fear the aircraft would lose GPS signal and attempt to return to its home point. (Note the “return to home” fail-safe routine was disabled for this set of flights.) Remarkably, the results were favorable because the unmanned aircraft was able to maintain sufficient GPS signal for flight assistance, and rarely did the pilot notice marked degradation in its sensor assistance.

It should be recognized that not all pilots will be comfortable to fly in close proximity to structures. A pilot should not be pressured into flying in conditions in which he or she is not comfortable. The best recommendation for becoming comfortable with flying in all conditions is to repeatedly practice flying the UAS until all controls and maneuvers become natural and intuitive. This will allow the pilots to collect the best imagery possible under minimum stress.

Some of the imagery collected during these 28 flights are shown below, resulting primarily from manual flights with sensor-assistance using the cruise control tool equipped on the senseFly albris.

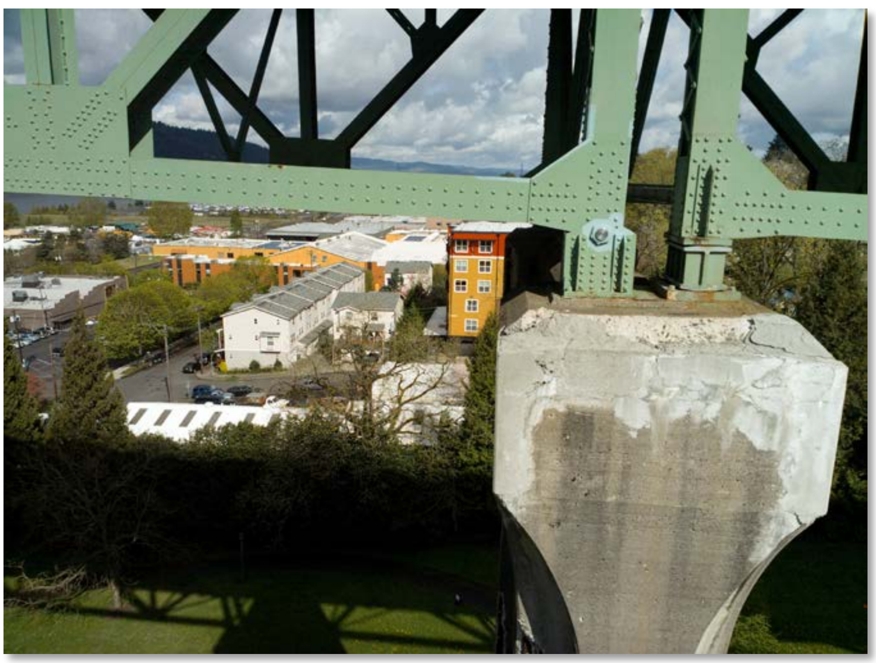


Figure 4.57: South pin connection on top of bent 11. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.58: Spalling with exposed metal on bent 11. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.59: Looking under the south side of span 10. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.60: Looking under the North West side of span 10. Note the conduit failure. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.61: North pin connection on top of bent 11. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.62: Spalling on top of the north side of bent 11 with exposed metal. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.63: Under the south east soffit of span 8. Note the areas where the paint has been refinished is very noticeable. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.64: South pin connection on top of bent 8. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.65: Top east side of bent 8. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

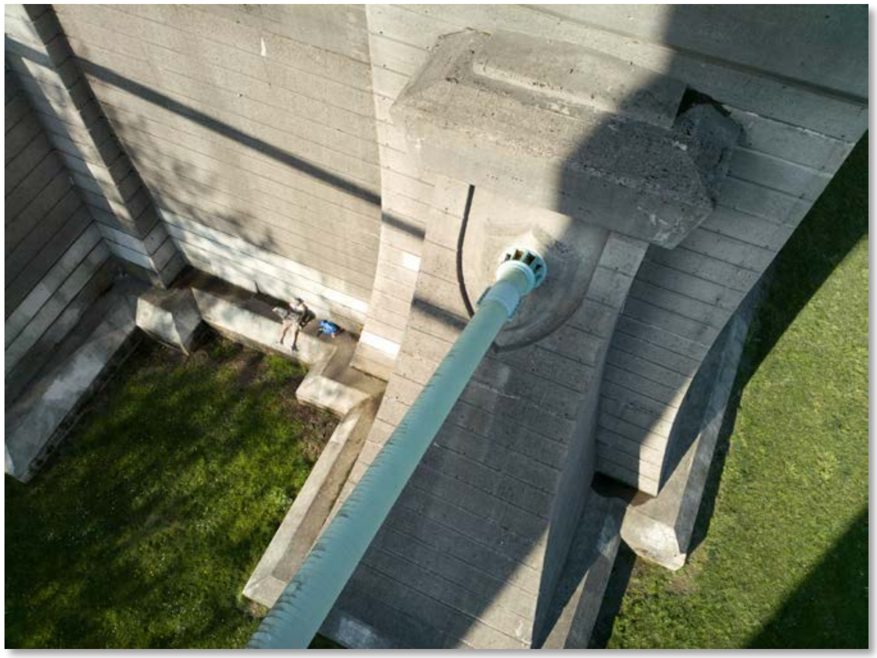


Figure 4.66: South east anchorage and cable. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.67: South bearing pad connection on top of bent 7. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.68: Traverse cracking with efflorescence in deck soffit at southeast end of span 6. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.69: Cross bracing and traverse cracking with efflorescence in deck soffit in span 7. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.70: Top east side of bent 7 showing spalling with exposed metal at the top of the arch. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.71: Traverse cracking with efflorescence in deck soffit at southeast end of span 6. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.72: Connection for span 6 (right) to south side of east tower. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.73: Looking under the deck at the northwest connection of span 5 to the east tower. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.74: North side of the East tower footing. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.75: Gusset plate connection in span 5. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.76: Gusset plat and suspension cable connection near south mid span 5. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.77: Looking under span 5. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.78: Looking under span 5. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.79: Looking under mid span 7 where the south cable crosses the span. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.80: North east side of span 6. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.81: Looking under span 5. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.82: North east side of span 6 connection at bent 7. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.83: Looking under the deck at the northwest connection of span 5 to the east tower. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

Figure 4.84: Looking under the deck at the northeast connection of span 6 to the east tower. Taken from senseFly albris main HD camera. Focal length: 8 mm, 35mm equivalent: 25 mm. (Full image)

4.2 TEST TOWER INSPECTIONS

4.2.1 Woodburn Tower

UAS test inspection flights were conducted of the Woodburn Tower Site, located approximately 3 km north-northwest of Woodburn, Oregon. This tower is in a storage yard and is owned and managed by Marion County. This site has a single communication tower on the north east corner of the site. The tower is a 3-leg, self-supporting steel structure with a height of 53 meters and has five antennas installed at various heights and different orientations on the frame. Figure 4.85 shows the Marion County tower for inspection.

Figure 4.85: Woodburn Marion County Communication Tower

The objective of this flight was for the project team to familiarize themselves with the workflow of flying communication towers. This was the first tower the team had flown and various manual flight methods using both aircraft platforms available (i.e. the senseFly albris, and DJI S900) were completed. As discussed in chapter 3, if imagery is collected with sufficient overlap, it is possible to align and orthorectify the photos to produce a 3D point cloud and orthophoto using SfM software. The best method to ensure overlap is to utilize waypoint-assisted flights. SenseFly's *eMotion X* (senseFly albris) and 3D Robotics' *MissionPlanner* (S900) software were used for planning rectangular overhead flights for capturing nadir photos of the site. The objective was to later stitch these photos together to create a map and digital elevation model of the site.

The senseFly albris was next used to collect oblique, close-up images of the tower. To collect these images, a waypoint-assisted flight pattern was developed wherein the tower was approximated as a cylinder with a diameter of 3 meters. Then, a flight pattern was constructed in *e-Motion X* so that the aircraft would fly in circles around and with an offset distance of approximately 15 to 20 meters from this cylinder model (with the camera pointed at the tower). Each circle was roughly spaced every 5 to 10 meters up the tower.

While flying on the backside of the tower, where the tower was between the GCS and aircraft, the team experienced brief instances (less than 3 seconds) of loss of communication between the GCS and the unmanned aircraft. Such a situation can be dangerous, as the aircraft could attempt to fly to its home point and accidentally collide with the tower which was blocking its straight path to its home point. Flying structures where obstacles can interfere with the communication between ground control and the unmanned aircraft should be avoided. If they cannot be avoided then the pilot should be completely aware and have contingencies in place for possible emergency landings. In this case, the danger was mitigated by setting the aircraft to fly upward to an elevation above the tower prior to attempting to return to its home point if the data link is lost.

Some of the example imagery collected from the way-point assisted flights are shown below. The resulting overlapping imagery was post-processed in *Agisoft Photoscan* to develop a 3D point cloud, orthophoto, and digital terrain model of the project site.

Figure 4.86: Various antenna mounted on Woodburn Tower. Taken with senseFly albris (Full image)

Figure 4.87: Various antenna mounted on Woodburn Tower. Taken with senseFly albris (Full image)

Figure 4.88: Top of Woodburn Tower. Taken with senseFly albris (Full image)

Figure 4.89: Top view looking down. Taken with Sony a5000 mounted on the S900 (cropped image)

Figure 4.90: Top view of tower. Taken with senseFly albris (cropped image)

Figure 4.91: Point cloud model of tower created using Agisoft Photoscan

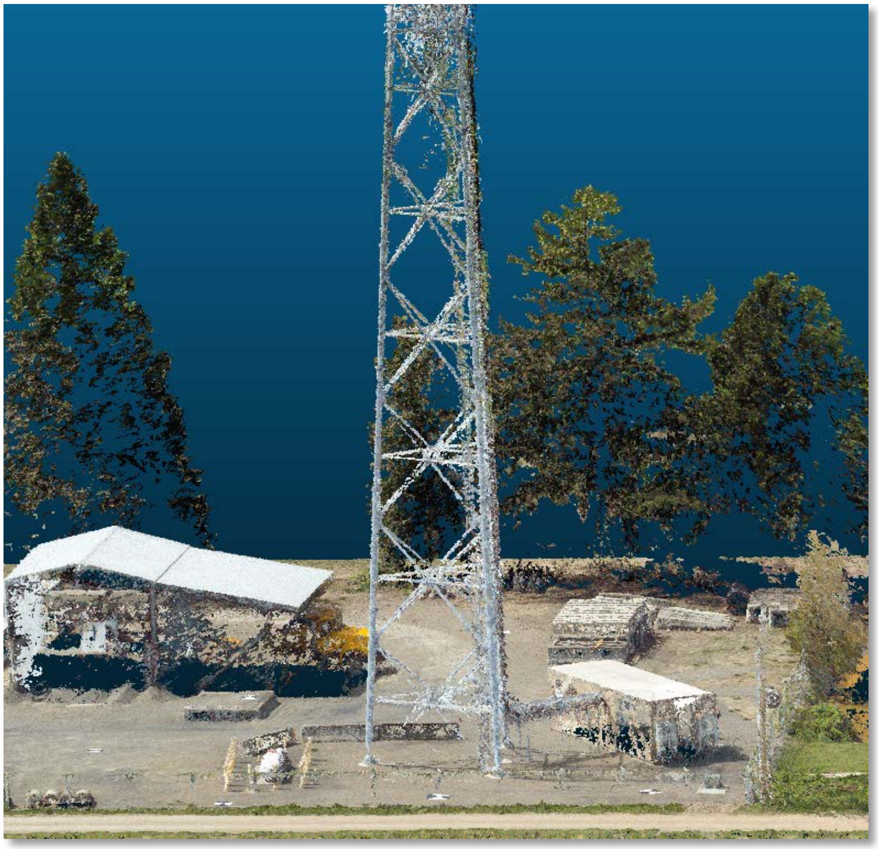


Figure 4.92: Point cloud model of tower created using Agisoft Photoscan

Figure 4.93: Digital surface model of the site created using Agisoft Photoscan.

4.2.2 Washburn Butte Tower

UAS test inspections were also conducted at Washburn Butte, located approximately 6 km north of Brownsville, Oregon. This site has five different communication towers at its summit. The towers range in size, type, and shape. The eastern most tower at Washburn Butte is managed by ODOT (Figure 4.94), and it was the focus of the inspection flights.

Figure 4.94: Washburn Butte ODOT Communication Tower

The tower is an "A-Frame" tower with a square base. The tower is 48.8 m tall and has eight antennas installed at various heights and different orientations on the frame. The objective of the flights around the Washburn Butte Tower was to gather high-resolution imagery for inspection, and also to create a 3D point cloud and aerial orthophoto of the site. Waypoint-assisted flights were selected because they enable a systematic collection of data for ensuring adequate photo overlap. SenseFly's *eMotion X* software was used for planning both a cylindrical flight plan for systematically capturing oblique photos around the tower (Figure 4.95a) and an overhead, rectangular flight plan for capturing nadir photos of the site (Figure 4.95b). At each waypoint (i.e., gray cone) depicted in this figure, the camera on the UAS was automatically triggered.

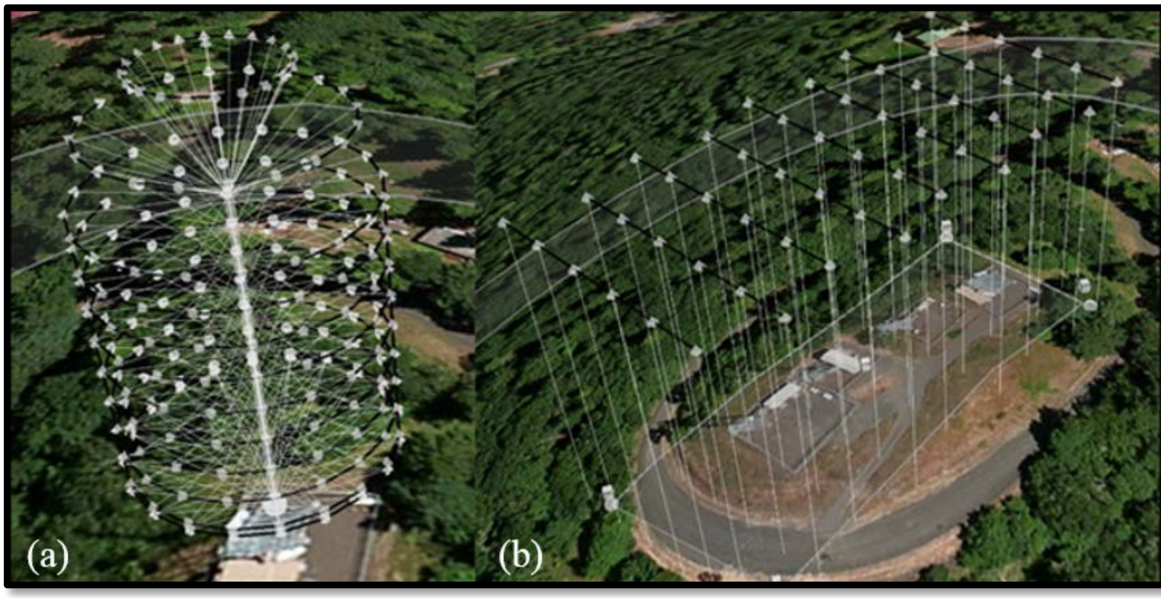


Figure 4.95: Flight Plans for Washburn Butte Tower: (a) cylinder flight plan for capturing oblique imagery of the tower; (b) rectangular overhead flight plan for capture nadir photos of the site

The overhead flights were planned at 57 m AGL with an image overlap of 80%. This flying height is higher than the tallest obstacles on the sight for safe operations, but it remains low enough to provide an aerial orthophoto with a 1-cm horizontal resolution for the site.

Using *eMotion X* software, the cylindrical flight plan was more difficult to program while maintaining a close standoff distance from the tower in order to acquire very high-resolution imagery for inspection. Using the cylindrical flight plan tool, the software only allows the user to change the location and size of the cylinder and the desired resolution and overlap of the imagery. The software estimates the imagery resolution and overlap as if photos were taken of the cylinder. Ideally, a cylinder should be fitted to approximate the location and size of the tower, then waypoints should be calculated in order to achieve very high-resolution photos for inspection (e.g., ≤ 1 mm/px) with around 80% overlap. Unfortunately, the highest resolution that the software allows for planning purposes is 2.5 mm/px; using this setting, the software computes waypoints with a large standoff distance of over 15 m. (Note that this overly large standoff distance was used during the inspection of the Woodburn Tower.) To overcome this issue and capture closer photos of the tower for inspection, the team planned the center of the cylinder in the center location of the tower, then shrunk its diameter to the smallest possible setting in the software (i.e., 1 m, as shown in Figure 4.95a). This effectively resulted in waypoints that were much closer to the tower, enabling the capture of higher-resolution photos at a closer standoff distance. However, the software computes the necessary number of imaging waypoints to achieve a desired overlap on the design cylinder, not the tower which is much closer to the camera. To help account for this, the overlap for the cylinder flights was increased, arbitrarily, to 85 percent in order to collect more overlapping data.

Table 4.3: Summary of the Final Settings Used for the Waypoint Mission Planning in the eMotion X software at Washburn Butte

Setting	Value
Cylinder diameter	1 m
Cylinder height	45 m
Resolution	0.25 cm/px
Overlap	85%
Standoff distance to cylinder*	14 m

*Note that the standoff distance from the tower was much less (i.e., 3-4 m) than from the design cylinder

A control survey was completed to establish GCPs so that a 3D model from SfM processing could be output in a defined coordinate system. Prior to the flights, multiple aerial targets were evenly distributed throughout the project site. Each aerial target was positioned using a total station and GNSS receiver receiving corrections from the Oregon Real-Time GNSS Network (ORGN).

Some of the example imagery collected from the way-point assisted flights of the tower are shown below. These images were uploaded in Agisoft Photoscan, and a 3D point cloud, orthophoto, and digital terrain model of the site was developed by post-processing. During post-processing, the coordinates at each of the GCPs from the site survey were uploaded and the aerial targets were identified in the images. The northings and eastings of the final point cloud is in 1983 Oregon North Zone State Plane Coordinates (NAD 83(2011) Epoch 2010.00) and the orthometric heights are referenced to NAVD 88.

Figure 4.96: Antenna and its connection at the Washburn Butte Tower

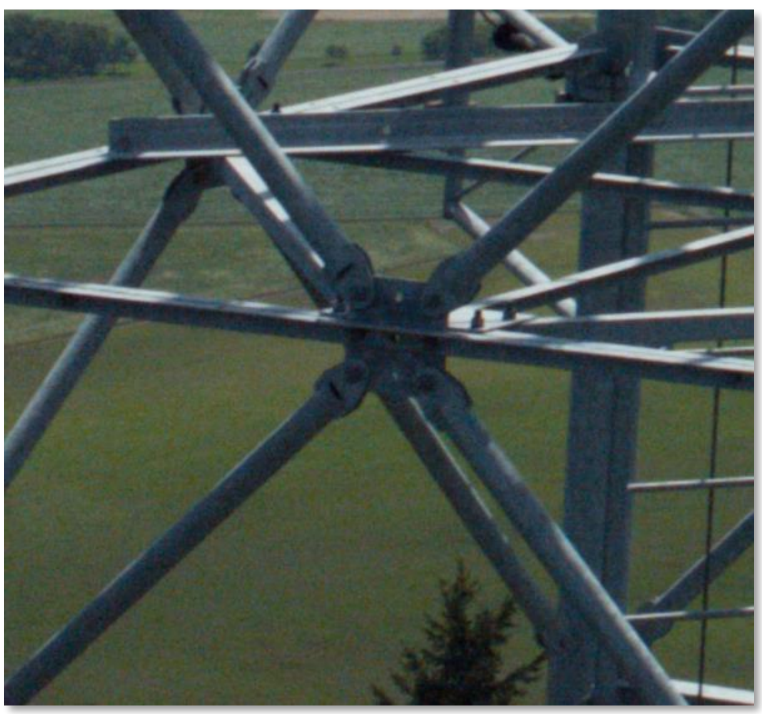


Figure 4.97: Member cross bracing connection at the Washburn Butte Tower. Notice it is possible to identify missing bolts at this connection

Figure 4.98: Antenna connection at the Washburn Butte Tower

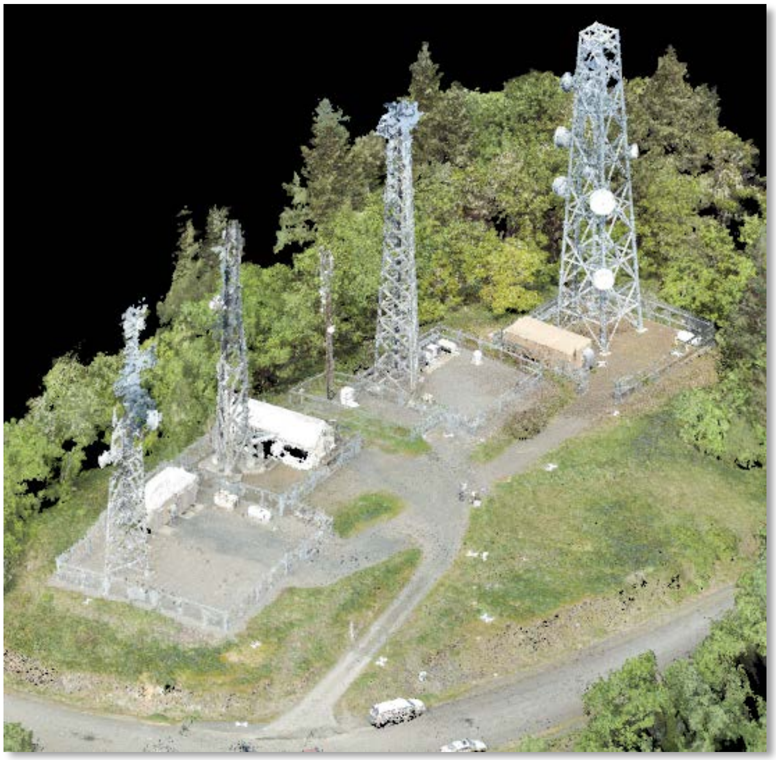


Figure 4.99: Point cloud model of the multiple towers on top of Washburn Butte created using Agisoft Photoscan. The objective was to map the tower managed by ODOT, which is right-most tower in the scene with a complete cloud of points

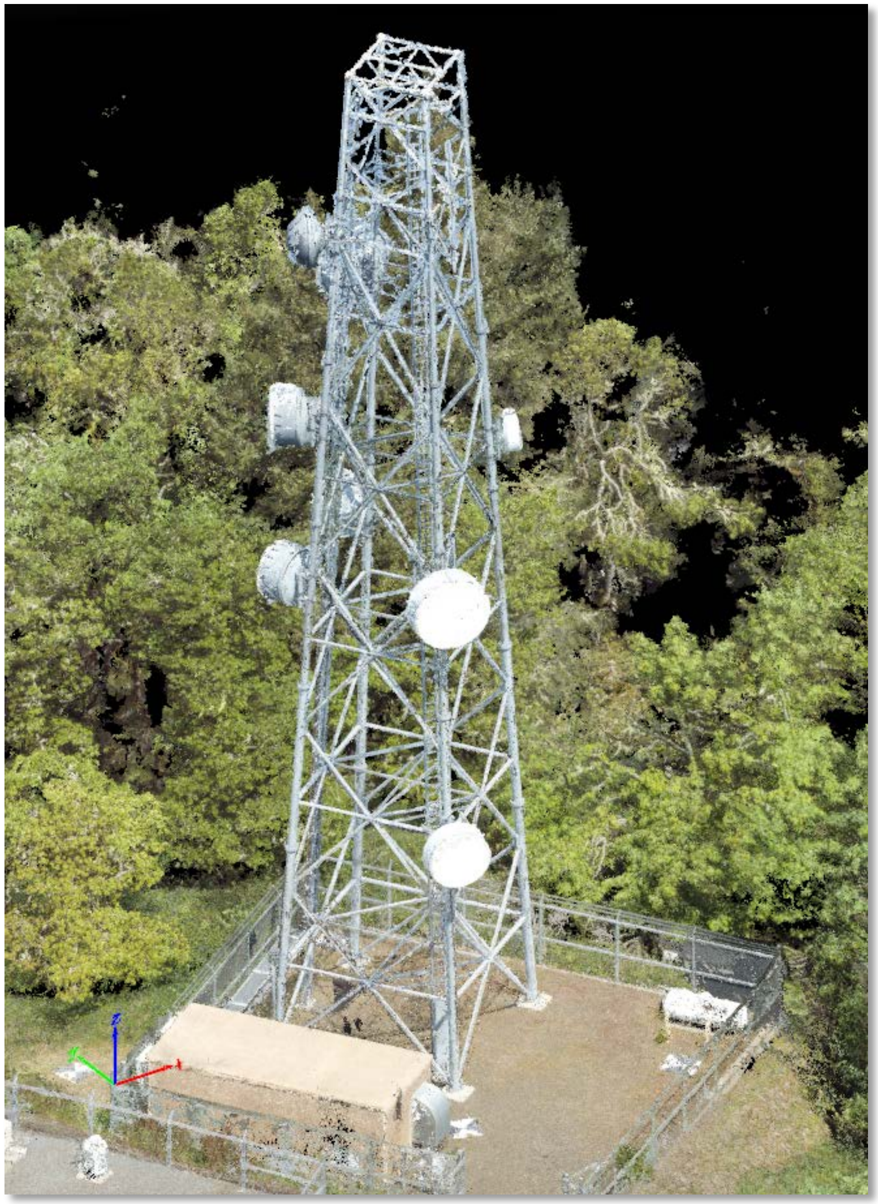


Figure 4.100: Point cloud model of ODOT tower at Washburn Butte

Figure 4.101: Close-up point cloud model of ODOT tower at Washburn Butte

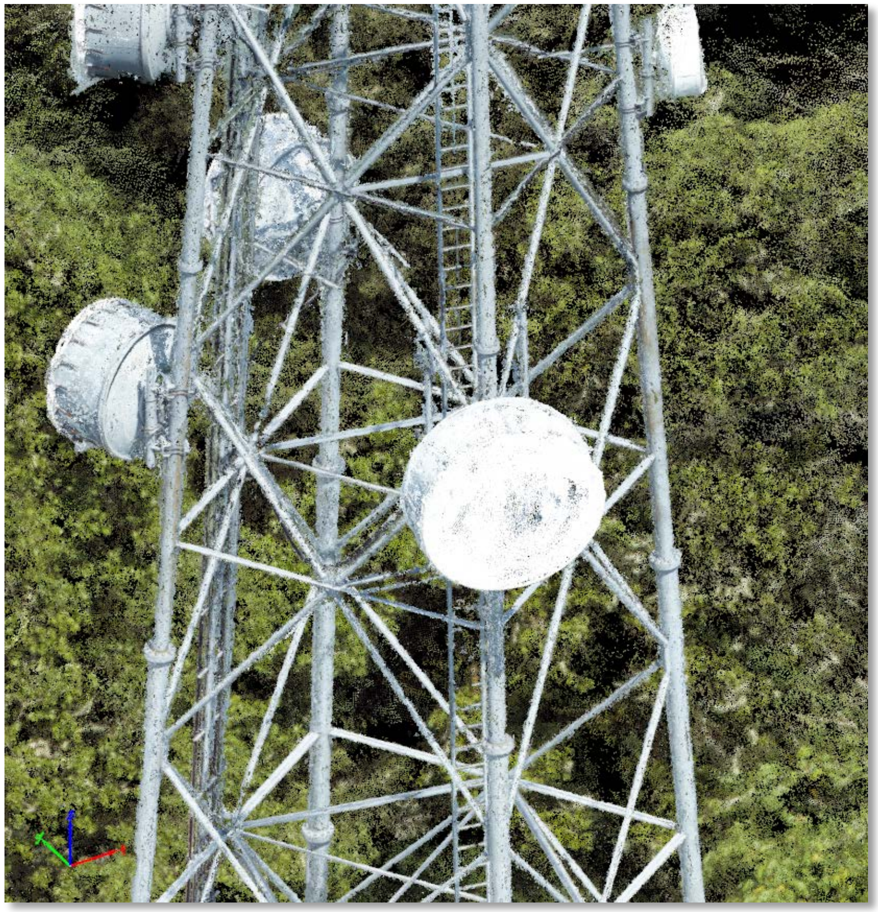


Figure 4.102: Point cloud model of various antenna on ODOT tower at Washburn Butte

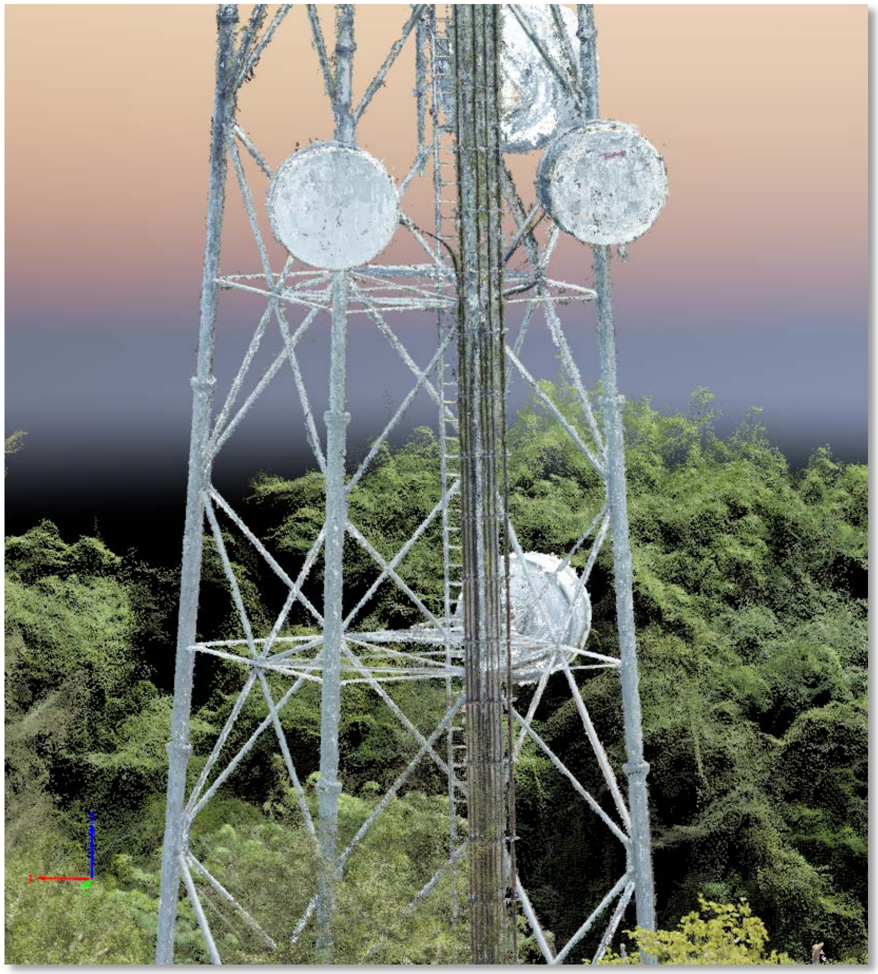


Figure 4.103: Point cloud model of cabling on ODOT tower at Washburn Butte

4.2.3 Corvallis Maintenance Site Tower

Additional UAS test inspection flights were conducted of the Corvallis Maintenance Tower, located at ODOT's District 4 maintenance yard at the address of 3700 SW Philomath Blvd in Corvallis, Oregon. The inspected tower is the only tower on the site and was selected for this study due its ease of access and close proximity to Oregon State University. Figure 4.104 is a photograph of the selected tower for inspection.

Figure 4.104: Corvallis Maintenance Tower

The tower is a rectangular tower with a square base. The tower is 27.4 m tall and has 2 antennas installed at various heights with different orientations on the frame.

The objective of the flights around the Corvallis Maintenance Tower was to collect high-resolution imagery around the tower for inspection purposes. As opposed to the flight method used at the Washburn Butte Tower, consisting of waypoint-assisted flights, the mission consisted entirely of manual flights with sensor assistance. The manual flight method allowed the pilot to fly the aircraft with a radio controller and ensure imagery was collected at specific areas of interest. The pilot used first-person view technology in order to position the UAS and ensure that imagery of desired components on the tower were acquired. As a simple test, prior to the flights, an ODOT inspector loosened a bolt on the tower without disclosing its location to the team in order to see if it could be detected and identified in the UAS inspection.

All of the flights were completed with the senseFly albris. Some of the imagery collected from the manual flights with sensor-assistance are shown below.

Figure 4.105: Antenna connection at the Corvallis Maintenance Tower

Figure 4.106: Loose bolt on northwest column of the Corvallis Maintenance Tower. (Note ODOT loosened this bolt as a blind test on if it could be detected during a UAS inspection.)

Figure 4.107: Top view of the Corvallis Maintenance Tower

Figure 4.108: Communication cable mount on the Corvallis Maintenance Tower

4.2.4 Grizzly Mountain Tower

UAS test flights were also attempted at Grizzly Mountain, located in rural Central Oregon, approximately 30 km northeast of Terrebonne and 23 km northwest of Prineville. This site has over ten communication towers at its peak with numerous differing signals. The towers range in size, type, and shape on the site. Figure 4.109 shows the ODOT tower for inspection, which is the eastern-most tower at the site.

Figure 4.109: Grizzly Mountain Communication Towers

The ODOT tower is a lattice “A-Frame” tower with a square base. The tower is 40 m tall and has 9 antennas installed at various heights with different orientations on the frame. Similar to the Washburn Butte Tower, the objective of the flights around the Grizzly Mountain Tower was to gather high resolution imagery and create a 3D model using SfM software. The team intended to collect imagery using a “hybrid” method, combining waypoint-assisted flights, as completed at the Washburn Butte Tower, supplemented with manual flights with sensor assistance of the tower, as completed at the Corvallis Maintenance Tower. The project team believed this flight plan would provide the best results by producing imagery with sufficient overlap and coverage of the tower using the waypoint-assisted flights while also providing more detailed imagery of high-interest areas using the manual flight mode with sensor assistance.

Unfortunately, flights were not able to be initiated due to significant interference of the data link signals between the GCS and aircraft. After numerous attempts using all of the available frequencies on-board the UAS, a reliable data link could not be established. At the site, an ODOT inspector used a spectrum analyzer, and it was determined that the Wireless Internet Service Provider (WISP) towers at the site were the cause of the frequency interference. This issue underscores the importance of completing a thorough investigation of a proposed site at different times throughout the day in order to reduce the possibility of signal interference during a mission. WISP towers pose a significant problem for UAS that operate in the 2.4 and 5.0 GHz frequencies, because they spread strong signals intermittently across these frequency limits.

5.0 DISCUSSION AND ANALYSIS OF RESULTS

The test flights attempted and completed at the sites discussed in chapter 4 have shown promising results in the capabilities of using UAS as a tool for inspection of both bridges and towers. During the completion of these sites, the data acquisition and processing strategies have been continually evaluated, refined, and retested. The imagery shown in this report show examples of the level of detail that can be acquired with a UAS using the flight methods discussed in chapter 3 (although some resolution and detail is lost when pasting the high definition images in this report). Depending on the lighting, the collected data successfully shows rust, paint patches, loose/missing bolts and rivets, and cracks as small as a few millimeters in width.

Based on detailed analysis of the data and results from all of the data acquisitions summarized previously, this chapter documents the optimal acquisition parameters, as well as the elements of a structural inspection that can be satisfied with UAS. Additionally, the results of a cost-benefit analysis on the use of UAS for bridge inspection is presented in this chapter.

5.1 OPTIMAL FLIGHT AND ACQUISITION PARAMETERS

The flight parameters that were investigated and refined during the flight missions described in chapter 4 include: flight mode, flying speed, camera pointing angle, camera field of view, and aircraft standoff distance from structure. Summarizing from (and adding to) the master's thesis of Matt Gillins (Gillins 2016), an OSU graduate student formerly supported on this project, the following sections list the parameters investigated and the resulting recommendations from this work.

5.1.1 Flight Mode

Three modes of flight were investigated in this research: 1) manual, 2) manual with sensor assistance, and 3) waypoint-assisted. It was determined that flight modes 2 and 3 (sensor-assisted and waypoint-assisted) are the most beneficial for bridge and tower inspection, with waypoint-assisted being best for overhead, vertical imagery acquisition for the purposes of mapping the entire project site and sensor-assisted being best for flying alongside the structure in order to capture very highly resolute imagery for inspection. The authors recommend using both methods for each structural inspection to take advantage of the benefits of each. Occasionally, the structure being inspected or other nearby objects can block GPS signals to the point that neither of these flight modes is possible, although such a case was not encountered in this project. In such a challenging case, fully manual mode is the only option. Therefore, remote aircraft PICs conducting structural inspections should be proficient in all three modes of operation and should be prepared to take control of the aircraft manually (via the controller) at any time during a flight, if necessary.

5.1.2 Standoff Distance

Due to the need to collect highly resolute imagery as discussed above, operators must fly the UAS very close to the structure. However, as the standoff distance decreases the stress becomes greater for the pilot due to the increased chance of the structure obstructing or degrading satellite signals, and sudden wind gusts (which are common around some bridges), which can push the unmanned aircraft uncontrollably toward the structure. At the same time, it is advantageous to remain close to the structure to obtain high-resolution imagery and, as necessary, make use of a headlamp on the unmanned aircraft when the natural lighting on the structure is inadequate. In working with the senseFly albris, it was determined that an approximate standoff distance of 3 to 5 m achieved a balance of pilot comfort and image resolution. Note that this distance varies for each individual pilot and the current weather conditions. However, there were times when it would have been preferable to obtain even higher-resolution imagery. For those applications, it is recommended that an optical zooming camera is used, even if the unmanned aircraft is equipped with other sensors (e.g., ultrasonic sensors) to assist in maintaining safe standoff distances. The project team completed multiple flights of one bridge with a custom DJI S900 hexacopter equipped with a digital camera with a 30x optical zoom (i.e., Sony WX 500). The optical zoom enabled collection of higher resolution imagery while keeping a safer standoff distance of 5 to 10 m. Flying at a larger standoff distance improves the safety of the flight and reduces the likelihood of crashing; however, it does reduce the effectiveness of using a headlamp for collecting imagery of features in a shadow.

If attempting to fly underneath a structure (e.g., beneath a bridge deck), satellite signal may be completely blocked. GPS sensors are commonly installed on a UAS for assisting the operator during flight. When flying a multicopter, GPS enables the aircraft to hover in place. GPS is also used to navigate the aircraft during pre-programmed Waypoint-Assisted Missions. When flying underneath or in close-proximity to the bridge, the satellite signals may not be reliable. In these instances, flying at a larger standoff distance with an optical zooming camera and/or using a unmanned aircraft equipped with additional flight-assistance sensors are needed. Additional flight-assistance sensors could include ultrasonic sensors which can be used to detect obstacles or hold the aircraft at a fixed distance from a structural member.

UAS technology is rapidly unfolding, and many individuals are developing new enhancements to improve the piloting of an aircraft near obstacles. This report is limited to the UAS that are currently available. However, it is obvious that in the near future, newer UAS will be developed and the technology will continue to improve. Some individuals are developing tools for tracking a UAS with a robotic total station rather than relying so heavily on GPS. Other developments are also underway for taking advantage of artificial intelligence techniques, inexpensive lidar sensors, computer vision techniques, sonar, and more so that an unmanned aircraft could automatically (or nearly automatically) “sense” and “avoid” obstacles during flight. When these newer sense-and-avoid technologies emerge and become common on UAS, the piloting of unmanned aircraft for inspections of structures will become easier.

5.1.3 Flying Speed

The sensor-assisted flights alongside structures were conducted with a constant, strafing flying speed (<1 m/s) to acquire high-resolution imagery from a viewing angle only possible if a conventional inspection were performed with a snooper crane or using climbers. A major advantage of multi-rotor aircraft is the ability to hover in place (i.e., flying speed ~0) when requested by the inspector. When the standoff distances were much larger (> 15 m), such as for the overhead mapping flights, slightly higher flying speeds (3-5 m/s) were implemented for efficiency. Flying speed did not seem to be a major hindrance on production, but flying faster than these speeds could result in blurry images

5.1.4 Camera Pointing Angle

No single camera pointing angle was found to be optimal for all aspects of all inspections. Rather, it was determined that a camera with a gimbal allowing variable pointing angle proved advantageous for inspection. Unlike the Phantom 3 Pro, where the camera is mounted beneath the rotors, the senseFly albris used by the project team on many of the inspections conducted in this work has this capability, employing a front-mounted camera held on a gimbal that can tilt from zenith (straight up) to nadir (straight down). River bank mapping and overhead flights were conducted with a near-nadir viewing geometry to obtain near-vertical imagery. Meanwhile, for imaging cracks in concrete, connections, bearing locations, and rusted pins, it was often beneficial to use its gimbal to orient the camera such that its optical axis was closer to horizontal and viewing the imagery in real-time on the FPV monitor. In order to inspect the bottom of the bridge deck, the camera also needed to be pointed upward in a zenith or near-zenith orientation.

5.1.5 Camera Parameters

Bridge and tower 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 highly resolute imagery is further compounded during an in-depth inspection where 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) estimates 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:

$$S = R\theta \tag{5-1}$$

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 0.13 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 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:

$$S = \frac{S_w \cdot R}{f \cdot P_w} \tag{5-2}$$

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

During the flights, the closest standoff distance of the aircraft from the bridge was roughly 3 m. Setting R = 3000 mm in Eqn. 5.2 and P_w = 4096 pixels, the spatial resolution (S) is estimated to equal 1.26 mm/pix. This resolution, although highly resolute, is still ten times coarser than the estimated spatial resolution of the human eye at arm's length. Multiplying the spatial resolution, S, with P_w will equal the field of view width (fov) for the camera. At S = 1.26 mm/pix, the camera will have fov = 5.142 m.

In order to meet the estimated spatial resolution of the human eye at arm's length, this camera would need to have a standoff distance of only 0.308 m. Its fov at this small spatial resolution of 0.13 mm/pix will be 0.528 m.

The intrinsic parameters of the primary cameras used in this research are documented in Table 5.1. All cameras used in this study enabled very high-resolution imagery to be acquired; however, none of them meet the resolution of the human eye at arm's length 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. As previously stated, an optical zoom feature may enable collection of higher-resolution imagery without the need to fly so close to the structure. Additional considerations with optical zoom include: 1) decrease in image stability in the zoomed-in image (i.e., the image appearing to jump around without a highly gyro-stabilized mount), 2) the difficulties in using SfM software if the focal length changes in flight, and 3) inability to use headlamps when too far back from the structure.

Table 5.1: Camera Parameters for the Primary Cameras Used in this Research

Camera Model	S_w (mm)	f (mm)	P_w (Pix)	S if R = 3 m (mm/pix)	R required for S = 0.13 mm/pix* (m)	fov for S = 0.13 mm/pix* (m)
senseFly albris HD Camera	9.90	8.0	7152	0.52	0.746	0.923
Sony a5000	23.20	16.0	5456	0.80	0.486	0.704
Sony WX 500	6.17	4.1	4896	0.92	0.420	0.632
DJI Phantom 3 Pro Camera	6.17	3.6	4096	1.26	0.308	0.528

* Spatial resolution of the human eye at typical arm's length distance was estimated to be 0.13 mm.

5.1.6 Weather Conditions

While weather is an important consideration in any aircraft operation, wind has been found in this research to be an especially critical factor in structural inspections with remote aircraft. 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. In strong wind environments a heavier multicopter is better suited. Regardless of the aircraft being used, this issue is complicated when flying in close proximity to the bridge as sudden wind gusts can push any aircraft toward the structure. Bridges over wide rivers or canyons are commonly in natural "wind tunnels" and complicated wind eddies can form near the bridge. A key recommendation from this work is that, if wind speeds are significant enough to noticeably affect the performance of the aircraft, the flight should be aborted and the aircraft should be landed (Gillins 2016). It is difficult to list a single wind speed that will meet the abort criterion, as it is a function of aircraft weight and power, pilot comfort, and potentially other variables. Therefore, it is recommended that the flight crew establish the wind-speed threshold for each aircraft through test flights conducted before inspecting a structure. As an extra safety precaution, the crew should also launch the aircraft and examine its ability to resist wind gusts at an inspection site prior to flying it close to the structure.

Two other parameters, cloud cover and sun angle, were found to be extremely important to image quality. 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 fair to poor when capturing imagery underneath the bridge deck. The use of flash lights or headlamps could help alleviate this issue, and real time tools could be developed for changing the aperture size of the camera during flight. Although best results can be obtained when the illumination conditions were favorable at the time of acquisition, computer science tools (e.g., local contrast enhancement) could be explored and potentially used to post-process and enhance the quality of the UAS-derived imagery. The post-processing tends to work best when edits are applied directly to the raw imagery.

5.1.7 Flight Planning for Future Post-Processing

By using carefully planned, waypoint-assisted flight missions, it is possible to capture imagery with satisfactory resolution and sufficient overlap for future SfM post-processing. One of the major challenges of UAS structural inspections is that it results in a large volume of imagery which can be difficult to keep organized. A helpful solution to this issue is a byproduct of creating a 3D point cloud of the structure using SfM software. During SfM processing, the images are placed relative to each other (or "aligned"). Some software, such as *Pix4DMapper* and *Agisosft Photoscan,* provide a tool that allows the user to view each image that was used to reconstruct a selected point in the point cloud. Figure 5.1 shows an example screenshot of the software tool in *Pix4DMapper*. As shown, the user selected a point near a connection on the Crooked River Bridge, and the software displayed on the right pane each photo that was used to reconstruct the selected point. Figure 5.2 shows a similar screenshot after the user selected a point in the point cloud for the Washburn Butte Tower.

This by-product of SfM processing is useful for keeping imagery organized and for documenting the work completed during an inspection. This function is also very useful when virtually inspecting a structure as it allows the user to know exactly where the object in the photo is in relation to the structure, which is a difficulty when looking at large volumes of images with nearly identical members throughout the structure.

Note, if the members of the structure are too similar, then the SfM algorithm will have a difficulty properly determining the position and orientation of each image. This issue can be mitigated by increasing the standoff distance from the structure to increase the field of view of the resulting images. For best results for future SfM processing and photo alignment, it is recommended to begin flying a site at a fairly distant standoff distance (e.g., 50 m), then conduct additional flights and slowly reduce the standoff distance until within the desired distance for capturing the high-resolution, detailed imagery of the structure for inspection. This procedure of beginning with a large standoff distance and then slowly reducing the standoff distance for each flight will enable the SfM software to align the images for 3D reconstruction.

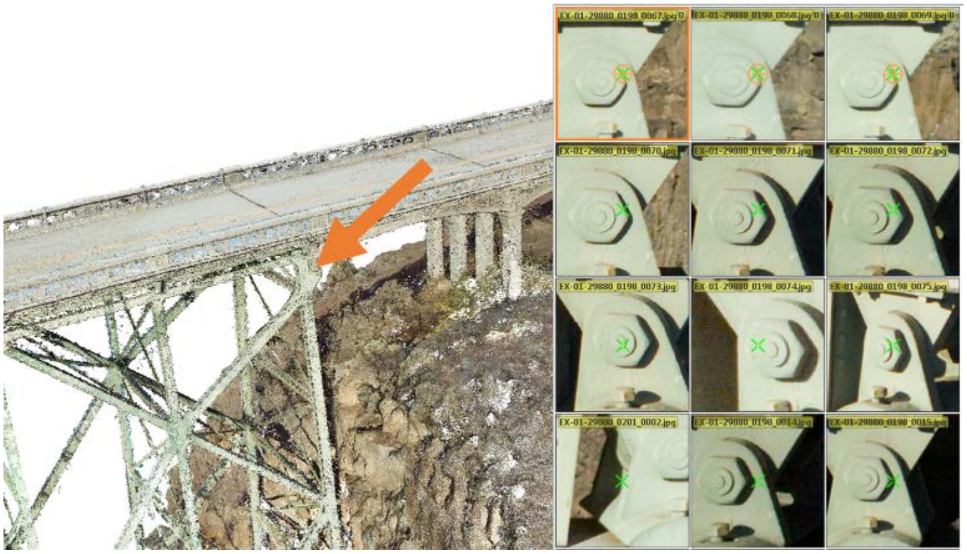


Figure 5.1: Screen shot of a method for viewing all photos taken of a bolt on the Crooked River Bridge. Pix4Dmapper shows all photos of the selected point on the right pane of the window

Figure 5.2: Screen shot of a method for viewing all photos taken of a bolt on the Washburn Butte Tower

5.2 BRIDGE INSPECTION REQUIREMENTS SUITABLE TO UAS

AASHTO defines eight different types of 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 inspection used to search and identify any defects on the bridge. If defects or damage are found, in-depth or damage inspections are then prescribed. In-depth and damage inspections have a more "hand's on" requirement in which probing, scraping, and contacting the bridge is necessary. Since it is currently not possible to probe, scrape, and contact the bridge with a UAS, UAS mostly benefit the visual portion of routine inspections. (However, some developments are underway for UAS to become capable in the near future to attaching and probing a structure.) Below lists details on each of the eight different types of bridge inspections per AASHTO.

- Initial Inspections – inspection that sets the baseline for all future inspections. Primarily it is done visually.
- Routine Inspections – regularly scheduled inspections that are done to determine if additional inspections are needed.
- Damage Inspections – inspections that are scheduled after damage is found during a routine inspection. It is designed specifically around the damage that was identified
- In-depth Inspections – In-depth inspections are scheduled inspections that include "hands on" inspections including 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.

The FHWA requires that every bridge inspection is accompanied with a bridge inspection report. The report requires the inspector to provide specific "inventory" items, assign "condition" ratings, and rate "appraisal" items for each bridge (Ryan et al., 2008). Below is a list of inventory ratings that describe permanent characteristics of the bridge and only change when the bridge is altered in some way, such as reconstruction or change in load restriction.

- 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 and include an assessment of the bridge deck, superstructure, and substructure. Required 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, fascias, 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.

Appraisal items are used to evaluate a bridge in relation to the level of service which it provides on its highway system, such as its clearances, geometry, and alignments. Required 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."

The results of the test UAS bridge inspections, as well as a detailed review of UAS and payload specifications, were used to assess, item-by-item, which of the previously listed and required reporting elements of an FHWA inspection report can or cannot be aided by a UAS. A rating system on a 1-4 scale was used to designate 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 5.2-5.5. Tables 5.2 through 5.4 rate how well a UAS assists with the inventory, condition rating, and appraisal elements of a bridge inspection report. Table 5.5 rates how well a UAS helps with each of the aforementioned eight different types of AASHTO bridge inspections.

Table 5.2: Bridge Report Inventory Items UAS can Facilitate

Report Requirement	Rating (1-4)*	How it 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 and this information should be known prior to an inspection; 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	1	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.

* Rating scale: 1 = not useful; 2 = limited use; 3 = useful; 4 = very useful

Table 5.3: Bridge Report Condition Ratings UAS can Facilitate

Report Requirement	Rating (1-4)*	How it aids or why it cannot
Deck	4	Geometry of Deck as well as presence of defects could be identified via high resolution imagery. One challenge to imaging the tops of bridge decks is the requirement that the UAS not fly directly above the bridge deck or over nonparticipants.
Superstructure	4	Presence of cracks and other defects can be identified as well as monitored though imagery collected from 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

* Rating scale: 1 = not useful; 2 = limited use; 3 = useful; 4 = very useful

Table 5.4: 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

* Rating scale: 1 = not useful; 2 = limited use; 3 = useful; 4 = very useful

Table 5.5: 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. (However some newer UAS are under development that are capable of diving underwater as well as flying. In the near future, UAS may also benefit underwater inspections of a bridge.)
Routine Wading	2	Bank inspections can be surveyed in ways not previously done for points of view that an inspector couldn't normally reach. 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.

* Rating scale: 1 = not useful; 2 = limited use; 3 = useful; 4 = very useful

5.3 COST BENEFIT ANALYSIS

The cost benefit analysis in this project was conducted through a multi-step process. First, baseline costs for bridge inspections conducted without the use of UAS were established by compiling existing data from ODOT. Next, the project team's findings from the previous tasks and conversations with ODOT personnel were used to establish which project costs could be reduced through use of UAS and to estimate percent reductions in those categories. A guiding principle in this step was to avoid overestimating cost savings, given the complexity of large bridge inspections and the fact that UAS are only one tool at the inspectors' disposal. The third step in the process was to determine the percentage of bridges that ODOT inspects that are suitable for UAS inspection. The necessity of this step lies in the fact that not every bridge can be inspected with UAS. For example, some bridges are in controlled airspace (i.e., other than Class G airspace), in close proximity to populated areas, or too close to vegetation, power lines or other obstructions to safely conduct UAS flights. The average cost savings per bridge was then multiplied by the number of bridges inspected by ODOT per year and by the percentage of bridges suitable for UAS inspection to arrive at a total estimated annual cost savings. Under the assumption that a State DOT, such as ODOT, might purchase three new UAS per year to support a UAS program, the cost of three UAS (based on the cost of the senseFly albris owned and operated by the OSU project team) was considered as a project cost. Other project costs considered in this analysis included maintenance and disk space for storing the large volumes of imagery collected in a UAS-assisted inspection. Finally, a benefit-cost ratio was computed.

The step of establishing the baseline costs for a bridge inspection done without UAS was accomplished using 33 bridge inspection cost spreadsheets provided by ODOT Bridge Coordinator and TAC Member, Erick Cain. From the original list of 33 cost spreadsheets, 15 were selected for which the cost breakdowns were sufficiently detailed to enable itemized analysis of the various costs associated with an inspection. The names of all contracting firms and subcontractors were removed ahead of time from the spreadsheets, and the data was aggregated to preserve anonymity of the firms involved in the inspections and to omit any information that could be considered proprietary. The 15 bridge inspections covered by the remaining cost spreadsheets spanned a range of sizes, types and inspection durations.

The next step involved estimating the time and cost savings associated with use of UAS for some components of an inspection. For this step, an average or "representative" bridge inspection was considered to take seven days with two people. Since there is obviously a large variation in the time and scope of the inspections of different bridges (based on bridge size, materials, condition, etc.), these averages were based on discussions with Erick Cain regarding the bridges inspected by the project team in Central Oregon. The cost categories considered for reduction (or, increase) when employing UAS in an inspection include:

1. Personnel time (field and office)

2. Equipment rental/usage (e.g., snooper trucks)

3. Traffic control

4. Travel (including lodging, meals and incidentals)

The in-field inspection time was estimated to be reduced by 20% for bridges suitable for UAS inspection, but with an associated increase in office time of 30% (due to flight planning and data downloading, processing and analysis tasks). Based on the average office and field times from the 15 cost spreadsheets, applying these percentage increases and decreases yielded an overall reduction in personnel time of 10% (Table 5.6). It was assumed that if the average in-field time savings per project is 20%, then as a result equipment rental and traffic control costs will also decrease by 20% per project. At an estimated cost of $2,000 per day for snooper truck rental, and $2,500 per day for traffic control, this resulted in a significant decrease in field inspection costs.

Table 5.6: Estimated Personnel Time Benefits (costs) through UAS Use

	Personnel Time Saved (%)	Dollars Saved ($)
Average:	10%	3,900
Std. Dev:	3%	2,700
Min:	3%	200
Max:	15%	10,500

From the data compiled from the cost spreadsheets, the average cost of a bridge inspection was $73,800 without using UAS. As summarized in Table 5.7, by implementing UAS, there is an estimated average savings of approximately $3,900 for personnel time, $2,800 for equipment rental, and $3,500 for traffic control, resulting in a decrease in bridge inspection costs of $10,200 per project for those bridges suitable for UAS usage.

Table 5.7: Estimated Decrease in Bridge Inspection Cost per Project Where UAS is Suitable

Category	Estimated Savings
Personnel Time:	$3,900
Equipment Rental:	$2,800
Traffic Control:	$3,500
Total Estimated Saving:	$10,200

For estimating the UAS costs, it was assumed that ODOT (or another State DOT interested in using UAS in bridge inspection) would purchase three remote aircraft similar in cost to the senseFly albris procured by the OSU project team and used in the majority of the inspections in this project. OSU's purchase order (P0100846, serial number: EX-01-29880) was executed on November 16, 2015. The cost of the aircraft and accompanying equipment (batteries, propeller set, radio modem, remote control, etc.), as well as operator training and software, was $39,079. (As an aside, it is worth noting that, as with all technology, UAS costs are expected to decrease and capabilities to increase over time).

Two other considerations are worth noting here. The first is that if an FAA CFR Part 107 certified Remote Pilot in Command (PIC) is needed on the project team, this could add one additional member of the project team with additional associated travel costs. However, in our analysis, it was considered that one current member of the inspection team would obtain the Part 107 certification and would serve as the Remote PIC. Secondly, it is important to note the shift in personnel time from field to office that can occur when implementing UAS. This has safety implications that extend beyond cost savings, as office work can generally be conducted more safely than field operations. For this preliminary cost-benefit analysis, the enhanced safety that can result from this shift from field to office time was not specifically accounted for, but it is nevertheless worth emphasizing as an important benefit of UAS.

If a dedicated pilot (with remote pilot certificate, as specified in Part 107 of the Federal Aviation Regulations) is needed, this adds one additional person to the inspection team, increasing lodging and per diem costs. However, if at least one member of the inspection team is certified and can serve as the pilot in command, then there are no additional personnel or travel costs associated with this item.

5.3.1 Assessment of Percentage of Bridges Amenable to UAS Surveys

ODOT provided a list of 1460 bridges inspected over a two-year span (approximately 730 bridges inspected annually). From the full list of 1460 bridges, the team randomly selected a subset of 80 bridges on which to perform UAS feasibility analysis. This UAS suitability analysis entailed analyzing the airspace around each bridge (OSU's COA as well as Part 107 rules only permit flights within Class G airspace, without waivers, which can take 90 days to obtain, even if granted), as well as examining potential takeoff and landing zones, and identifying obstructing vegetation or other potential challenges for UAS flights. All bridges selected in the subset were studied remotely using Google Earth and Google Street View. The results from this analysis estimates that 16 percent of bridges would benefit from being supplemented by UAS inspection. Figure 5.3 shows a map of the 80 bridges in this assessment, and it depicts which bridges seem amenable for UAS inspection.

It should be noted that 56 percent of the bridges were rejected because UAS would not be necessary for inspection due to small size and low clearance heights. The team assumed these small, short bridges can easily be inspected by foot. The results from the feasibility analysis allowed the team to estimate the percentage of bridges for which supplemental UAS inspection are suitable.

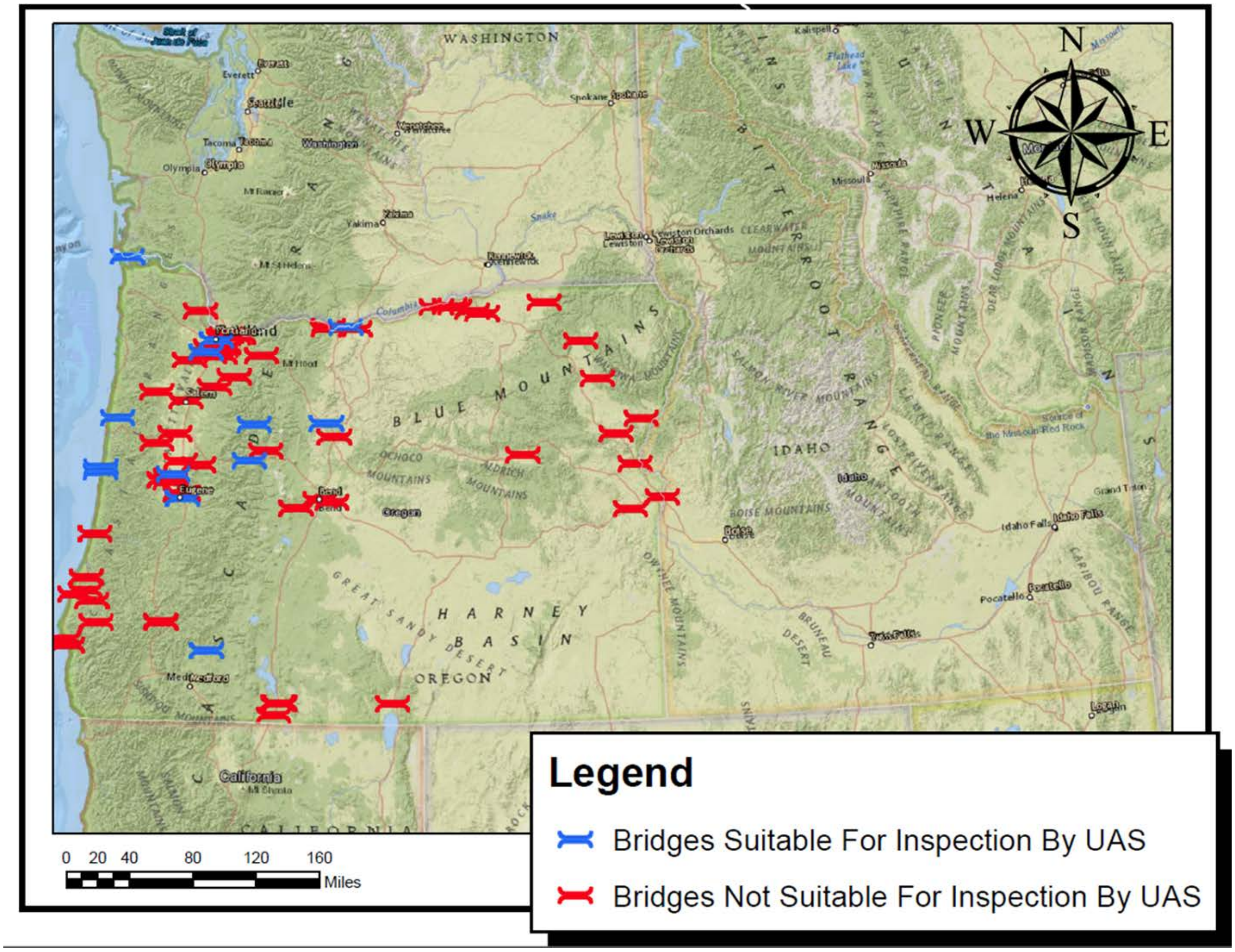


Figure 5.3: Map of 80 randomly selected bridges evaluated for potential suitability for UAS inspection in Oregon

5.3.2 Benefit Cost Ratio

A simplified benefit-cost ratio calculation was performed as follows. First, the annual benefits of implementing UAS in inspections were quantified as the product of the following variables: 1) the average cost savings per bridge from use of UAS, 2) the number of bridge inspections conducted by ODOT annually, and 3) the fraction of bridges suitable for UAS use, yielding:

$$B = \$10{,}200(730 \times 0.16) = \$1{,}191{,}360 \quad (1)$$

The cost estimate was then obtained by summing three costs: 1) the cost of purchasing three UAS, 2) the annual maintenance cost, and 3) the cost of disk space (redundant network storage) for storing one year of imagery. As noted above, the UAS cost, based on OSU's procurement of the albris, is assumed to be \$39,079; hence three UAS are \$117,237. Based on the OSU project team's experience, the annual maintenance costs for three UAS and peripheral equipment are estimated at \$4,500. For the storage space calculation, we assume: 675 photos per project (based on the average for the 6 bridges flown by OSU thus far) and 117 bridge inspections suitable for UAS. Photos are on average 10 MB each. Raw photos are on average 45 MB each. Thus the total disk space requirement is estimated as:

(117 bridges per year)(675 photos per bridge)(0.01 GB per jpeg photo) = 790 GB per year

If the raw format is kept as well (recommended procedure), then the total is 4,750 GB or 4.750 TB per year. The cost per TB is taken to be $1,200 and is based on fast-access, redundant network storage costs at OSU. This brings the total cost for disk space to $5,700. Summing the three considered costs yields:

$$\sum C = \$117{,}237 + \$4{,}500 + \$5{,}700 = \$127{,}437$$

In more robust benefit-cost analysis, discount rates must be considered especially since with most new programs the costs tend to be up-front while the benefits accrue over time. However, for purposes of this study, a simplified approach is taken in which discount rates are not considered. The benefit-cost ratio is:

$$BCR = \frac{\$1{,}191{,}360}{\$127{,}437} = 9.3$$

Due to the number of simplifying assumptions in this analysis and the uncertainty in a number of the estimates, this estimated benefit-cost ratio should be used with an appropriate level of caution. Nevertheless, the large BCR provides strong indication of positive return on investment (ROI) for implementing UAS in ODOT’s Bridge and Tower Programs. The analysis should be refined and updated after implementation of a UAS inspection program, where numbers representing the costs and benefits are more certain and clearer. A number of assumptions and estimations needed to be made simply because a UAS inspection program has not yet been implemented.

6.0 CONCLUSIONS

Interest in the use of UAS in bridge inspections is growing rapidly, due to the potential to reduce costs and enhance safety. The ability to maneuver a sUAS into a specific location relative to the bridge and to use onboard, gimbal-mounted cameras to acquire high-resolution video and still imagery for both real-time analysis and post-processing makes UAS an attractive technology to aid in inspections, as it can facilitate inspection of locations on the structure that may be difficult, costly and/or dangerous to access. However, in deciding whether to implement use of UAS in bridge inspections and in developing operational procedures, transportation agencies require information on both the capabilities and limitations of UAS, as well as the regulatory aspects of UAS, and the associated costs and benefits. This report documents the results of a two-year research project to investigate the effectiveness of using small unmanned aircraft systems (sUAS) in bridge inspection. Although the primary focus was on inspecting bridges, the utility of UAS for inspecting wireless communication towers was also investigated.

Following a literature review and analysis of UAS characteristics favorable for structural inspection work, unmanned aircraft and associated sensors and other equipment were obtained and used to acquire imagery in six bridge inspections (two at St. Johns Bridge, and one each at Independence, Crooked River, Mill Creek, and Winchester Bridges) and three tower inspections (Woodburn Tower, Corvallis Maintenance Tower, and Washburn Butte Tower). Based on analysis of the results, it can be concluded that by following the recommended procedures, UAS can be highly beneficial tool in inspection of many bridges and towers.

Specific findings from this project related to bridge inspections include:

- The UAS flight modes that are most advantageous for bridge inspection are sensor-assisted (for work alongside the bridge) and waypoint-assisted (for overhead mapping), but unmanned aircraft pilots must be proficient in entirely manual flight, due to the possibility of losing GPS around and under tall structures, such as bridges.

- While aircraft that provide assistance in maintaining a fixed standoff distance from a structure through use of ultrasonic sensors and navcams are highly beneficial for bridge inspection, there are many times when the pilot will feel uncomfortable operating so close to the bridge. For this reason, cameras with optical zoom are recommended for obtaining the highest-resolution imagery of critical features.

- Multicopter UAS with front-mounted, variable-tilt cameras are advantageous for bridge inspection.

- Cracks, pack rust, connections, hardware and bearing locations were all determined to be readily-identifiable in the imagery collected in this project after following the recommended flight procedures.

- Wind condition is the most important environmental variable in operating UAS in close proximity to bridges, but illumination conditions (sun angle, cloud cover and visibility) and camera settings (ISO, f-stop and focal length) are critical to obtaining high-quality imagery. UAS bridge inspection flight crews should have at least a basic level of expertise in photography to ensure acquisition of high-quality imagery.

- UAS can assist to varying degrees in many required elements of a bridge inspection and are very well suited for initial and routine inspections and for satisfying report requirements related to geometry and structural evaluation. Currently, UAS are not beneficial for more in-depth inspections that require touching, probing, or scraping a bridge.

To conduct the cost-benefit analysis portion of this project, baseline costs for bridge inspection without the use of UAS were first assessed using cost data provided by ODOT. The percentage of bridges that ODOT inspects that are suitable for UAS inspection was estimated by accounting for airspace, bridge size, vegetation, and other logistical and regulatory considerations. Cost categories that were considered either reduction or increase included personnel time, equipment rental/usage, traffic control, travel, UAS procurement, maintenance, and file storage. Based on this analysis, the benefit-cost ratio (BCR) from implementing UAS in ODOT's Bridge Program was estimated to be approximately 9. While this result provides strong indication of positive ROI for implementing UAS in ODOT's bridge inspection program, it must also be noted that there is a significant amount of uncertainty in this estimate, arising from the small sample sizes of the data used and a number of simplifying assumptions in the calculations. Thus, recommendations for further work include revising the cost-benefit analysis as additional information becomes available from ODOT's current UAS projects.

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APPENDIX A

SAFETY PLAN WASHBURN BUTTE

Date of Assessment:	04/25/2016	Personnel:	Pilot in Command:	Tom Normandy
Structure Type:	Communication Tower		Primary Observer:	Matt Gillins
Location of Structure:	44°26’10.8” N 122°59’07.1” W		Other Spotters:	Farid Javadnejad Dan Gillins Chris Parrish
Owner of Structure:	ODOT			
Owner’s Contact info:	555 13th St NE Salem, OR 97301-6867 Phone (503) 986-2700		COA Number:	2015-AHQ-105-COA-TS
			Team ‘s Emergency Contact Number:	(818)-497-8576
Airport within 5 nm?	Yes: X	No:	Airport Manager:	Jacob Kropf
If Yes Which:	J & J airport		Manger Contact info:	(541)-766-6783
Distance from Airport:	3.2 nm		Radio Frequency Air Traffic Controller:	N/A UNICOM 123.0

Safety Inventory: Mark yes or no if any of the following hazards are potential for work site.

YES	NO	Equipment Hazards	YES	NO	Personal Hazards	YES	NO	Environmental Hazards
X		Nearby Vehicular Traffic		X	Twisting/Bending/Awkward Positions/ Heavy Lifting		X	Falling Debris
	X	Nearby Heavy Equipment Operations		X	Working Over water		X	Confined Space
	X	Transport/Launch of Boat/ATV/Etc.		X	Loose unstable footing	X		Weather Related
	X	Boat/Watercraft Operations	X		Slip/Trip/Fall Hazard	X		Live Stock/Wildlife
	X	ATV Operations		X	Ladders/Elevated Platforms	X		Transients
X		Other		X	Other		X	Other

Mitigation Technique: For every Yes marked above describe the ways this risk will be mitigated.

Identified Hazard	Mitigation Technique
Nearby Vehicular Traffic	Safety Vests will be worn by team. Very low traffic.

Equipment Other- Radio Freq. Jam	Monitor radio frequencies being transmitted during flights via android app. If frequencies are jamming switch to unused band.
Trip Hazards	Ensure good footing and identify any trip hazards prior to flights being performed.
Weather (rain/lightning)	Flights will not be performed during rain or during lightning events to prevent damage to equipment or operators.
Wildlife	Potential for animal collisions. Spotters will monitor nearby airspace and if birds/other wildlife approach UAS the team will land the UAS ASAP to avoid potential collision and crash.
Transients	Any signs of waste or dangerous objects on site will be identified and reported.
Special Considerations	Description

Site Map/Photos:

All operations will comply with the Certificate of Authorization listed on Previous Page. Any deviation from which will be approved by the FAA prior to operations and will be attached to back of this form.

This form as been reviewed and the safety plan has been approved for operations.

ODOT Representative

Oregon State University Representative

APPENDIX B

Example Letter of Agreement Attached

LETTER OF AGREEMENT

EFFECTIVE: 25 and 27 April 2016

SUBJECT: Unmanned Aircraft Systems (UAS) Operations in the vicinity of Vennell Airport.

1. **PURPOSE:** To notify the owner operator of Vennell Airport of UAS operations in the vicinity of the airport, operating under a FAA Certificate of Authorization.

2. SCOPE: The procedures herein apply only to UAS operations with the Sensfly eXom and DJI S900 on the 25 and 27 of April 2016.

3. UAS OPERATING AREA:
The UAS Operating Areas will be 4.6 miles north of the Vennell Airport.

4. RESPONSIBILITIES: Parties of this Letter of Agreement (LOA) shall ensure all personnel comply with its provisions.

5. SCHEDULING:

a. UAS operations are scheduled for the 25 of April 2016.

b. The 27 of April 2016 is an alternate day if the weather is prohibitive on the 25^{th}.

c. A NOTAM will be filed prior to the operations beginning by a University of Oregon rep.

6. PROCEDURES:

A. General.

(1) Two-way radio communication with the Pilot In Charge (PIC), Tom Normandy of VDOS Global will be available at all time via UNICOM 123.0. The PIC will have a cell phone as an alternate means of communication (818)-497-8576.

(2) All UAS operations shall be conducted under visual meteorological conditions (VMC). The PIC is responsible for checking current and forecast weather conditions and for maintaining appropriate cloud avoidance.

(3) All UAS operations will be conducted in close proximity to the 2 selected Communication Towers.

B. Observers.

Observers shall maintain visual contact with the UAS during all phases of flight. If the observer loses sight of the UAS while in operation, the following methodologies shall be employed:

(1) The observer shall communicate directly to the PIC when visual contact has been lost and that attempts to regain visual observation are being employed.

(2) The PIC shall contact traffic via UNICOM to inform them when visual contact with the UAS has been lost (more than three minutes) by the observers.

(3) Once visual contact of the UAS is reacquired, the observer will communicate to the PIC that visual contact has been re-established. If the PIC plans on resuming operations in the work area, then the PIC shall advise traffic on the UNICOM that visual contact has been made and UAS Operations will resume.

(4) If loss of visual contact of the UAS occurs during the recovery phase of flight, the UAS will continue its landing process until safely on the ground.

(5) The PIC will take action to ensure the UAS remains clear of the aircraft.

C. Distress/Emergency:

(1) In the event of an UAS emergency, the PIC shall contact traffic on the Corvallis Municipal Airport CTAF and immediately declare an emergency, the PIC shall advise the tower of the situation and their intentions. Note: Manned aircraft emergencies shall take priority over unmanned aircraft emergencies.

(2) The UAS PIC shall comply with all Corvallis Municipal Airport traffic instructions to accommodate a manned aircraft emergency.

g. Lost Link Procedures:

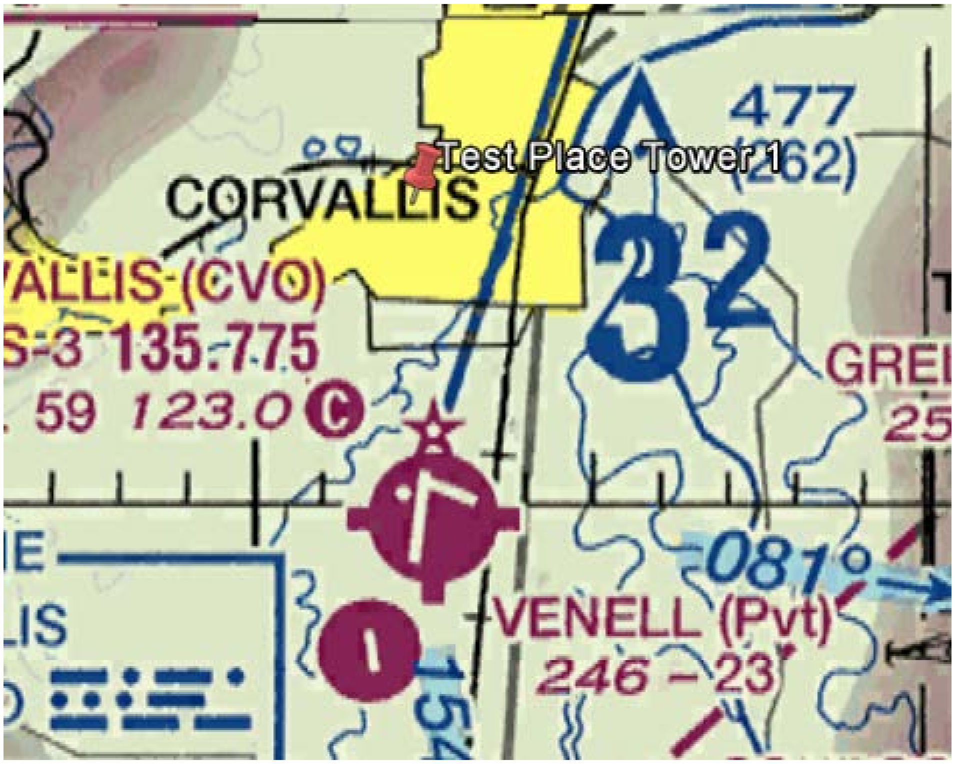
In the unlikely event of a lost link situation, the UAS will return to the launch site and land.

7. MISCELLANEOUS: Deviations from the procedures contained in this agreement shall be made only after coordination has been accomplished which completely defines responsibility in each case.

______________________	______________________
Clarence Venell	Christopher Parrish
Airport Manager	Oregon State University

Attachment 1

Flights will be conducted below
Below 200 feet AGL



APPENDIX C

Copy of OSU nationwide COA attached on next pages of report.

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

CERTIFICATE OF WAIVER OR AUTHORIZATION

ISSUED TO

Oregon State University

This certificate is issued for the operations specifically described hereinafter. No person shall conduct any operation pursuant to the authority of this certificate except in accordance with the standard and special provisions contained in this certificate, and such other requirements of the Federal Aviation Regulations not specifically waived by this certificate.

OPERATIONS AUTHORIZED

Operation of small Unmanned Aircraft System(s) weighting less than 55 lbs., in Class G airspace at or below 400 feet Above Ground Level (AGL) under the provisions of this authorization. See Special Provisions.

LIST OF WAIVED REGULATIONS BY SECTION AND TITLE

N/A

STANDARD PROVISIONS

1. A copy of the application made for this certificate shall be attached and become a part hereof.
2. This certificate shall be presented for inspection upon the request of any authorized representative of the Federal Aviation Administration, or of any State or municipal official charged with the duty of enforcing local laws or regulations.
3. The holder of this certificate shall be responsible for the strict observance of the terms and provisions contained herein.
4. This certificate is nontransferable.

Note-This certificate constitutes a waiver of those Federal rules or regulations specifically referred to above. It does not constitute a waiver of any State law or local ordinance.

SPECIAL PROVISIONS

Special Provisions are set forth and attached.

This certificate, 2016-WSA-101-COA, is effective from May 12, 2016 through May 11, 2018 and is subject to cancellation at any time upon notice by the Administrator or his/her authorized representative. Should a renewal become necessary, the Proponent shall advise the Federal Aviation Administration (FAA), in writing, no later than 45 business days prior to the requested effective date.

BY DIRECTION OF THE ADMINISTRATOR

FAA Headquarters, AJV-115
(Region)

Scott J. Gardner
(Signature)

May 11, 2016
(Date)

Acting Manager, UAS Tactical Operations Section
(Title)

COA Number: 2016-WSA-101

Issued To: Oregon State University, referred herein as the "Proponent"

Address: Mark Peters
A312 Kerr Admin
Corvallis, OR 97331

STANDARD PROVISIONS

A. General.

The review of this activity is based upon current understanding of Unmanned Aircraft System (UAS) operations and their impact on the National Airspace System (NAS).This Certificate of Waiver or Authorization (COA) will not be considered a precedent for future operations. As changes in, or understanding of, UAS operations occur, the associated limitations and conditions may be adjusted.

All personnel engaged in the operation of the UAS in accordance with this authorization must read and comply with the conditions, limitations, and provisions of this COA.

A copy of the COA including the special limitations must be immediately available to all operational personnel at each operating location whenever UAS operations are being conducted.

This COA may be canceled at any time by the Administrator, a person authorized to grant the authorization, or a representative designated to monitor a specific operation. As a general rule, this authorization may be canceled when it is no longer required, when there is an abuse of its provisions, or when unforeseen safety factors develop. Failure to comply with the authorization is cause for cancellation. All cancellations will be provided in writing to the proponent.

During the time this COA is approved and active, a site safety evaluation/visit may be accomplished to ensure COA compliance, assess any adverse impact on ATC or airspace, and ensure this COA is not burdensome or ineffective. Deviations, accidents/incidents/mishaps, complaints, etc. will prompt a COA review or site visit to address the issue. Refusal to allow a site safety evaluation/visit may result in cancellation of the COA. Note: This section does not pertain to agencies that have other existing agreements in place with the FAA.

Public Aircraft Operations are defined by statutes Title 49 USC §40102(a)(41) and §40125. All public aircraft operations conducted under a COA must comply with the terms of the statutes.

B. Airworthiness Certification.

The unmanned aircraft must be shown to be airworthy to conduct flight operations in the NAS. The proponent has made its own determination that the unmanned aircraft is airworthy. The unmanned aircraft must be operated in strict compliance with all provisions and conditions contained in the Airworthiness Safety Release (AWR), including all documents and provisions referenced in the COA application.

1. A configuration control program must be in place for hardware and/or software changes made to the UAS to ensure continued airworthiness. If a new or revised Airworthiness Release is generated as a result of changes in the hardware or software affecting the operating characteristics of the UAS, notify the UAS Integration Office via email at 9-AJV-115-UASOrganization@faa.gov of the changes as soon as practical.
   a. Software and hardware changes should be documented as part of the normal maintenance procedures. Software changes to the aircraft and control station as well as hardware system changes are classified as major changes unless the agency has a formal process accepted by the FAA. These changes should be provided to the UAS Integration Office in summary form at the time of incorporation.
   b. Major modifications or changes, performed under the COA, or other authorizations that could potentially affect the safe operation of the system, must be documented and provided to the FAA in the form of a new AWR, unless the agency has a formal process, accepted by the FAA.
   c. All previously flight proven systems, to include payloads, may be installed or removed as required and that activity must be recorded in the unmanned aircraft and ground control stations logbooks by persons authorized to conduct UAS maintenance. Describe any payload equipment configurations in the UAS logbook that will result in a weight and balance change, electrical loads, and or flight dynamics, unless the agency has a formal process, accepted by the FAA.
   d. For unmanned aircraft system discrepancies, a record entry should be made by an appropriately rated person to document the finding in the logbook. No flights may be conducted following major changes, modifications or new installations unless the party responsible for certifying airworthiness has determined the system is safe to operate in the NAS and a new AWR is generated, unless the agency has a formal process, accepted by the FAA. The successful completion of these major changes, modifications or new installations must be recorded in the appropriate logbook, unless the agency has a formal process, accepted by the FAA.
2. The unmanned aircraft must be operated in strict compliance with all provisions and conditions contained within the spectrum analysis assigned and authorized for use within the defined operations area.
3. All items contained in the application for equipment frequency allocation must be adhered to, including the assigned frequencies and antenna equipment characteristics. A ground operational check to verify that the control station can communicate with the aircraft (frequency integration check) must be conducted prior to the launch of the unmanned aircraft to ensure any electromagnetic interference does not adversely affect control of the aircraft.

C. Safety of Flight.

1. The Proponent or delegated representative is responsible for halting or canceling activity conducted under the provisions of this COA if, at any time, the safety of persons or property on the ground or in the air is in jeopardy, or if there is a failure to comply with the terms or conditions of this authorization.

2. Sterile Cockpit Procedures.

   a. No crewmember may perform any duties during a critical phase of flight not required for the safe operation of the aircraft.

   b. Critical phases of flight include all ground operations involving:

      1) Taxi (movement of an aircraft under its own power on the surface of an airport),

      2) Take-off and landing (launch or recovery), and

      3) All other flight operations in which safety or mission accomplishment might be compromised by distractions.

   c. No crewmember may engage in, nor may any pilot in command (PIC) permit, any activity during a critical phase of flight which could:

      1) Distract any crewmember from the performance of his/her duties, or

      2) Interfere in any way with the proper conduct of those duties.

   d. The pilot and/or the PIC must not engage in any activity not directly related to the operation of the aircraft. Activities include, but are not limited to: operating UAS sensors or other payload systems.

   e. The use of cell phones or other electronic devices is restricted to communications pertinent to the operational control of the unmanned aircraft and any required communications with Air Traffic Control.

3. See-and-Avoid.

   a. Unmanned aircraft have no on-board pilot to perform see-and-avoid responsibilities; therefore, when operating outside of active restricted and warning areas approved for aviation activities, provisions must be made to ensure that an equivalent level of safety exists for unmanned operations. Adherence to 14 CFR Part 91 §91.111, §91.113 and §91.115, is required.

      1) The PIC is responsible:

         - To remain clear and give way to all manned aviation operations and activities at all times,
         - For the safety of persons or property on the surface with respect to the UAS operation,
         - For ensuring that there is a safe operating distance between aviation activities and unmanned aircraft (UA) at all times, and
         - For operating in compliance with CFR Parts 91.111, 91.113 and 91.115

   b. The PIC is responsible to ensure that any visual observer (VO):

1) Can perform their required duties,
2) Are able to see the UA and the surrounding airspace throughout the entire flight, and
3) Are able to provide the PIC with the UA's flight path and proximity to all aviation activities and other hazards (e.g., terrain, weather, structures) sufficiently for the PIC to exercise effective control of the UA to prevent the UA from creating a collision hazard.

c. VO(s) must be used at all times and must maintain instantaneous communication with the PIC. Electronic messaging or texting is not permitted during flight operations.

d. The use of multiple successive VO(s) (daisy chaining) is prohibited.

e. VO(s) must be able to communicate clearly to the PIC any instructions required to remain clear of conflicting traffic.

f. All VO(s) must complete sufficient training to communicate to the PIC any information required to remain clear of conflicting traffic, terrain, and obstructions, maintain proper cloud clearances, and provide navigational awareness. This training, at a minimum, must include knowledge of:

1) Their responsibility to assist PICs in complying with the requirements of:
   - Section 91.111, Operating Near Other Aircraft,
   - Section 91.113, Right-of-Way Rules: Except Water Operations,
   - Section 91.115, Right-of-Way Rules: Water Operations,
   - Section 91.119, Minimum Safe Altitudes: General, and
   - Section 91.155, Basic VFR Weather Minimums
2) Air traffic and radio communications, including the use of approved air traffic control/pilot phraseology
3) Appropriate sections of the Aeronautical Information Manual (AIM)

g. The Proponent must not operate in Restricted Areas, Prohibited Areas, Special Flight Rule Areas or the Washington DC Flight Restricted Zone. Such areas are depicted on charts available at http://www.faa.gov/air_traffic/flight_info/aeronav/. Additionally, aircraft operators should beware of and avoid other areas identified in Notices to Airmen (NOTAMS) that restrict operations in proximity to Power Plants, Electric Substations, Dams, Wind Farms, Oil Refineries, Industrial Complexes, National Parks, The Disney Resorts, Stadiums, Emergency Services, Military or other Federal Facilities unless approval is received from the appropriate authority prior to the UAS Mission.

h. The unmanned aircraft will be registered prior to operations in accordance with Title 14 of the Code of Federal Regulations.

D. Reporting Requirements

1. Documentation of all operations associated with UAS activities is required regardless of the airspace in which the UAS operates. NOTE: Negative (zero flights) reports are required.
2. The Proponent must submit the following information on a monthly basis to

   9-AJV-115-UASOrganization@faa.gov :

   a. Name of Proponent, and aircraft registration number,

   b. UAS type and model,

   c. All operating locations, to include city name and latitude/longitude,

   d. Number of flights (per location, per aircraft),

   e. Total aircraft operation hours,

   f. Takeoff or landing damage, and

   g. Equipment malfunction. Required reports include, but are not limited to, failures or malfunctions to the:

      (1) Control station

      (2) Electrical system

      (3) Fuel system

      (4) Navigation system

      (5) On-board flight control system

      (6) Powerplant

3. The number and duration of lost link events (control, performance and health monitoring, or communications) per UAS, per flight.
4. Incident/Accident/Mishap Reporting

   After an incident or accident that meets the criteria below, and within 24 hours of that incident, accident or event described below, the proponent must provide initial notification of the following to the FAA via email at mailto: 9-AJV-115-UASOrganization@faa.gov and via the UAS COA On-Line forms (Incident/Accident).

   a. All accidents/mishaps involving UAS operations where any of the following occurs:

      1) Fatal injury, where the operation of a UAS results in a death occurring within 30 days of the accident/mishap

      2) Serious injury, where the operation of a UAS results in:

         - Hospitalization for more than 48 hours, commencing within 7 days from the date of the injury was received;
         - A fracture of any bone (except simple fractures of fingers, toes, or nose);
         - Severe hemorrhages, nerve, muscle, or tendon damage;

- Involving any internal organ; or
- Involves second- or third-degree burns, or any burns affecting more than 5 percent of the body surface.

3) Total unmanned aircraft loss
4) Substantial damage to the unmanned aircraft system where there is damage to the airframe, power plant, or onboard systems that must be repaired prior to further flight
5) Damage to property, other than the unmanned aircraft.

b. Any incident/mishap that results in an unsafe/abnormal operation including but not limited to

1) A malfunction or failure of the unmanned aircraft's on-board flight control system (including navigation)
2) A malfunction or failure of ground control station flight control hardware or software (other than loss of control link)
3) A power plant failure or malfunction
4) An in-flight fire
5) An aircraft collision involving another aircraft.
6) Any in-flight failure of the unmanned aircraft's electrical system requiring use of alternate or emergency power to complete the flight
7) A deviation from any provision contained in the COA
8) A deviation from an ATC clearance and/or Letter(s) of Agreement/Procedures
9) A lost control link event resulting in
   - Fly-away, or
   - Execution of a pre-planned/unplanned lost link procedure.

c. Initial reports must contain the information identified in the COA On-Line Accident/Incident Report.

d. Follow-on reports describing the accident/incident/mishap(s) must be submitted by providing copies of proponent aviation accident/incident reports upon completion of safety investigations.

e. Civil operators and Public-use agencies (other than those which are part of the Department of Defense) are advised that <u>the above procedures are not a substitute for separate accident/incident reporting required by the National Transportation Safety Board</u> under 49 CFR Part 830 §830.5.

f. For other than Department of Defense operations, this COA is issued with the provision that the FAA be permitted involvement in the proponent's incident/accident/mishap investigation as prescribed by FAA Order 8020.11, Aircraft Accident and Incident Notification, Investigation, and Reporting.

E. Notice to Airmen (NOTAM).

1. A distant (D) NOTAM must be issued prior to conducting UAS operations. This requirement may be accomplished:
    a. Through the proponent's local base operations or NOTAM issuing authority, or
    b. By contacting the NOTAM Flight Service Station at 1-877-4-US-NTMS (1-877-487- 6867) not more than 72 hours in advance, but not less than 24 hours for UAS operations prior to the operation. The issuing agency will require the:
        1) Name and address of the pilot filing the NOTAM request
        2) Location, altitude and operating area
        3) Time and nature of the activity.

Note: The NOTAM must identify actual coordinates and a Radial/DME fix of a prominent navigational aid, with a radius no larger than that where visual line of sight with the UA can be maintained. The NOTAM must be filed to indicate the defined operations area and periods of UA activity. NOTAMs for generalized, wide-area, or continuous periods are not acceptable.

FLIGHT STANDARDS SPECIAL PROVISIONS

Failure to comply with any of the conditions and limitations of this COA will be grounds for the immediate suspension or cancellation of this COA.

1. Operations authorized by this COA are limited to UAS weighing less than 55 pounds, including payload. Proposed operations of any UAS weighing more than 55 pounds will require the Proponent to provide the FAA with a new airworthiness Certificate (if necessary), Registration N-Number, Aircraft Description, Control Station, Communication System Description, Picture of UAS and any Certified TSO components. Approval to operate the new UAS is contingent on acknowledgement from FAA of receipt of acceptable documentation.

2. External Load Operations, dropping or spraying aircraft stores, or carrying hazardous materials (including munitions) is prohibited.

3. The UA may not be operated at a speed exceeding 87 knots (100 miles per hour). The COA holder may use either groundspeed or calibrated airspeed to determine compliance with the 87 knot speed restriction. In no case will the UA be operated at airspeeds greater than the maximum operating airspeed recommended by the aircraft manufacturer.

4. The Proponent should conduct and document initial training at a specific training site that will allow for the conduct of scenario-based training exercises. This training should foster a high level of flight proficiency and promote efficient, standardized coordination among pilots, visual observers, and ground crew members. To ensure safety and compliance, the training site should be is well clear of housing areas, roads, non-participating persons, and watercraft. When the Proponent has determined that

sufficient training scenarios have been completed to achieve an acceptable level of competency, the Proponent is authorized to conduct UAS public aircraft operations in accordance with Title 49 USC §§ Part 40125 at any location within the National Airspace System under the provisions of this COA.

5. The UA must be operated within visual line of sight (VLOS) of the Pilot in Command (PIC) and or the visual observer (VO) at all times. This requires the PIC and VO to be able to use human vision unaided by any device other than corrective lenses, as specified on their FAA-issued airman medical certificate or equivalent medical certification as determined by the government entity conducting the PAO. The VO may be used to satisfy the VLOS requirement as long as the PIC always maintains VLOS capability.

6. This COA and all documents needed to operate the UAS and conduct operations in accordance with the conditions and limitations stated in this COA are hereinafter referred to as the operating documents. The Proponent must follow the procedures as outlined in the operating documents. If a discrepancy exists within the operating documents, the procedures outlined in the approved COA take precedence and must be followed. The Proponent may update or revise the operating documents, excluding the approved COA, as needed. It is the Proponent's responsibility to track such revisions and present updated and revised operating documents to the Administrator or any law enforcement official upon request. The Proponent must also present updated and revised documents if they petition for extension or amendment to this COA. If the Proponent determines that any update or revision would affect the basis upon which the FAA granted this COA, then the Proponent must petition for an amendment to this COA. The FAA's UAS Integration Office (AFS−80) may be contacted if questions arise regarding updates or revisions to the operating documents.

7. The operating documents must be accessible during UAS operations and made available to the Administrator and/or law enforcement upon request.

8. Any UAS that has undergone maintenance or alterations that affect the UAS operation or flight characteristics, (e.g., replacement of a flight critical component), must undergo a functional test flight prior to conducting further operations under this COA. Functional test flights may only be conducted by a PIC with a VO and must remain at least 500 feet from other people. The functional test flight must be conducted in such a manner so as to not pose an undue hazard to persons and property.

9. The Proponent is responsible for maintaining and inspecting the UAS to ensure that it is in a condition for safe operation.

10. Prior to each flight, the PIC must conduct a pre-flight inspection and determine the UAS is in a condition for safe flight. The pre-flight inspection must account for all potential discrepancies (e.g. inoperable components, items, or equipment). If the inspection reveals a condition that affects the safe operation of the UAS, the aircraft is prohibited from operating until the necessary maintenance has been performed and the UAS is found to be in a condition for safe flight.

11. The Proponent must follow the UAS manufacturer's maintenance; overhaul, replacement, inspection, and life limit requirements for the aircraft and aircraft components.

12. Each UAS operated under this COA must comply with all manufacturer safety bulletins.

13. Government entities conducting public aircraft operations (PAO) involve operations for the purpose of fulfilling a government function that meet certain conditions specified under Title 49 United States Code, Section 40102(a)(41) & 40125(a)(2). PAO is limited by the statute to certain government operations within U.S. airspace. These operations must comply with general operating rules including those applicable to all aircraft in the National Airspace System. Government entities may exercise their own internal processes regarding aircraft certification, airworthiness, pilot, aircrew, and maintenance personnel certification and training. If the government entity does not have an internal process for PIC certification, an acceptable equivalent is that PIC shall hold

    a. Either an airline transport, commercial or private pilot certificate if UAS operations are within 5 nautical miles (NM) from an airport having an operational control tower, an airport having a published instrument flight procedure, but not having an operational control tower, or 2 NM from an airport not having a published instrument flight procedure or an operational control tower, or 2 NM from a heliport. The PIC must also meet the flight review requirements specified in 14 CFR § Part 61.56 in an aircraft in which the PIC is rated on his or her pilot certificate.

    b. For UAS operations outside of these locations the government entity may utilize a ground based training course and successful completion of a FAA written examination at the private pilot level or higher (or an FAA-recognized equivalent). The PIC must also hold a current 2nd Class FAA airman medical certificate or equivalent medical certification as determined by the government entity conducting the PAO.

14. The Proponent may not permit any PIC to operate unless the PIC demonstrates the ability to safely operate the UAS in a manner consistent with how the UAS will be operated under this COA, including evasive and emergency maneuvers and maintaining appropriate distances from persons, vessels, vehicles and structures. PIC qualification flight hours and currency must be logged in a manner consistent with 14 CFR § Part 61.51(b). Flights for the purposes of training the Proponent's PICs and VOs (training, proficiency, and experience-building) and determining the PIC's ability to safely operate the UAS in a manner consistent with how the UAS will be operated under this COA are permitted under the terms of this COA. However, training operations may only be conducted during dedicated training sessions. During training, proficiency, and experience-building flights, all persons not essential for flight operations are considered nonparticipants, and the PIC must operate the UA with appropriate distance from nonparticipants in accordance with 14 CFR § Part 91.119.

15. Pilots are reminded to follow all federal regulations (e.g. remain clear of all Temporary Flight Restrictions). Additionally, operations over areas administered by the National Park Service, U.S. Fish and Wildlife Service, or U.S. Forest Service must be conducted in accordance with Department of Interior/US Fish & Wildlife Service requirements.

(See 50 CFR §§ Part 27.34 and FAA Aeronautical Information Manual Section 4, paragraph 7-4-6.)

16. The presence of observers during flight operations, other than initial or recurrent pilot-in-command and visual observer training is authorized given compliance with the following provisions:

    a. Observers will receive a safety briefing that addresses the mission intent, safety barriers, non-interference with UAS mission personnel, and emergency procedures in the event of an incident or accident.

    b. Observers will be directed to, and contained within, a specific observation point that minimized the risk of injury and ensures that they do not interfere with the UAS mission.

    c. Observers must have a valid Federal Aviation Administration (FAA) second-class medical certificate issued under 14 CFR part 67; an FAA-recognized equivalent is an acceptable means of demonstrating compliance with this requirement.

    d. Proponent will ensure that observers do not engage in conversations, discussions, or interviews that distract any crewmember or mission personnel from the performance of his/her duties or interfere in any way with the proper conduct of those duties.

    e. Proponent will limit the number of observers to that which can be adequately monitored and protected by personnel and resources onsite.

    f. Operation will be conducted in compliance with ALL of the existing provisions, conditions and mitigations of this COA.

17. UAS operations may only be conducted during the daytime and may not be conducted during night, as defined in 14 CFR § Part 1.1. All operations must be conducted under visual meteorological conditions (VMC). Flights under special visual flight rules (SVFR) are not authorized.

18. The UA may not be operated less than 500 feet below or less than 2,000 feet horizontally from a cloud or when visibility is less than 3 statute miles from the PIC.

19. If the UAS loses communications or loses its GPS signal, the UA must return to a pre-determined location within the defined operating area.

20. The PIC must abort the flight in the event of emergencies or flight conditions that could be a risk to persons and property within the operating area.

21. The PIC is prohibited from beginning a flight unless (considering wind and forecast weather conditions) there is enough available power for the UA to conduct the intended operation and to operate after that for at least five minutes or with the reserve power recommended by the manufacturer if greater than five minutes.

22. Documents used by the Proponent to ensure the safe operation of the UAS and any documents required under 14 CFR § Part 91.9 and Part 91.203 must be available to the PIC at the UAS Ground Control Station any time the aircraft is operating. These documents must be made available to the Administrator or any law enforcement official upon request.

23. The UA must remain clear and give way to all manned aviation operations and activities at all times.
24. The UAS may not be operated by the PIC from any moving vehicle unless the government entity conducting PAO has determined that such operations can be conducted without causing undue hazard to persons or property and has presented such safety procedures to the FAA. Safety procedures include, but not limited to, emergency procedures, lost link procedures, and consideration of terrain and obstructions that may restrict the ability to maintain visual line of sight. Operations must also comply with all applicable federal, state and local laws pertaining to operations from a moving vehicle.
25. All flight operations must be conducted at least 500 feet from all nonparticipating persons, vessels, vehicles, and structures.

AIR TRAFFIC CONTROL SPECIAL PROVISIONS

A. Coordination Requirements.

1. Compliance with Standard Provisions, E. Notice to Airmen (NOTAM) satisfies the coordination requirement. Operator must cancel NOTAMs when UAS operations are completed or will not be conducted.
2. Coordination and de-confliction between Military Training Routes (MTRs) is the Proponent's responsibility. When identifying an operational area, the Proponent must evaluate whether an MTR will be affected. In the event the UAS operational area overlaps an MTR, the operator will contact the scheduling agency in advance to coordinate and de-conflict. Approval from the scheduling agency is not required.

B. Communication Requirements.

When operating in the vicinity of an airport without an operating control tower the PIC will announce operations on appropriate Unicom/CTAF frequencies alerting manned pilots of UAS operations.

C. Flight Planning Requirements.

This COA will allow small UAS (55 pounds or less) operations during daytime VMC conditions only within Class G airspace under the following limitations:

1. At or below 400 feet AGL, and
2. Beyond the following distances from the airport reference point (ARP) of a public use airport, heliport, gliderport, or water landing port listed in the Airport/Facility Directory, Alaska Supplement, or Pacific Chart Supplement of the U.S. Government Flight Information Publications:
    a. 5 nautical miles (NM) from an airport having an operational control tower, or
    b. 3 NM from an airport having a published instrument flight procedure, but not having an operational control tower, or
    c. 2 NM from an airport not having a published instrument flight procedure or an operational control tower, or
    d. 2 NM from a heliport.

3. The PIC is responsible for identifying the appropriate ATC jurisdiction nearest to the area of operations defined by the NOTAM.

D. Procedural Requirements.

This COA authorizes the Proponent to conduct UAS flight operations strictly within a "defined operating area" as identified under the required provision of Section E. Notice to Airmen (NOTAM) of this COA.

1. A "defined operating area" is described as a location identified by a Very High Frequency Omnidirectional Range (VOR) Radial/Distance Measuring Equipment (DME) fix. This location must have a defined perimeter that is no larger than that where visual line of sight with the UA can be maintained and a defined operational ceiling at or below 400' Above the Ground (AGL).
2. UAS operations must remain within this "defined operating area". The Proponent will discover and manage all risks and associated liabilities that exist within the defined operating area and all risks must be legitimately mitigated to assure the safety of people and property.
3. The UAS must remain within visual line of sight of the PIC and/or VO(s) at all times. The PIC and VO(s) must be positioned such that they can maintain sufficient visual contact with the UA in order to determine its attitude, altitude, and direction of flight. The PIC is responsible to ensure that the UA remains within the defined operating area. "Out of Sight", or "Behind the Obstruction" flight operations are prohibited.

E. Emergency/Contingency Procedures.

1. Lost Link Procedures:
   a. In the event of lost link, the UA must initiate a flight maneuver that ensures timely landing of the aircraft. Lost link airborne operations shall be predictable and the UA shall remain within the defined operating area filed in the NOTAM for that specific operation. In the event that the UA leaves the defined operating area, and the flight track of the UA could potentially enter controlled airspace, the PIC will immediately contact the appropriate ATC facility having jurisdiction over the controlled airspace to advise them of the UASs last known altitude, speed, direction of flight and estimated flight time remaining and the Proponent's action to recover the UA.
   b. Lost link orbit points will not coincide with the centerline of published Victor airways.
   c. The UA lost link flight track will not transit or orbit over populated areas.
   d. Lost link programmed procedures must de-conflict from all other unmanned operations within the operating area.
2. Lost Visual Line of Sight:

   If an observer loses sight of the UA, they must notify the PIC immediately. If the UA is visually reacquired promptly, the mission may continue. If not, the PIC will immediately execute the lost link procedures.

3. Lost Communications:

   If communication is lost between the PIC and the observer(s), the PIC must immediately execute the lost link procedures.

AUTHORIZATION

This Certificate of Waiver or Authorization does not, in itself, waive any Title 14 Code of Federal Regulations, nor any state law or local ordinance. Should the proposed operation conflict with any state law or local ordinance, or require permission of local authorities or property owners, it is the responsibility of the Oregon State University to resolve the matter. This COA does not authorize flight within in Restricted Areas, Prohibited Areas, Special Flight Rule Areas or the Washington DC Federal Restricted Zone (FRZ) without pre-approval, except operations in the Washington DC Special Flight Rule Area may be conducted in accordance with FDC NOTAM 6/0126. The Oregon State University is hereby authorized to operate the Unmanned Aircraft System in the National Airspace System.