Collection of Data with Unmanned Aerial Systems (UAS) for Bridge Inspection and Construction Inspection

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FOREWORD

This report documents research undertaken to explore the use of unmanned aerial systems (UAS) to support bridge inspection. It addresses UAS platforms and sensors used to assist or augment inspections, the data-collection needs to which UAS can contribute, and means and methods for managing the tremendous amount of data that can be collected by UAS-mounted sensors. The report also presents case studies that illustrate real-world applications of UAS for bridge inspections and the results of both field and laboratory testing geared toward establishing standards and requirements for UAS sensors that will ensure quality inspection products.

This report will be informative to bridge owners, engineers, and inspectors as well as UAS operators with an interest in bridge inspections. Additionally, the information in the report may be of interest to UAS sensor and system manufacturers as they continue to advance the technologies for the benefit of the transportation infrastructure industry.

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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	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

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	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS AND ACRONYMS

2D	two dimensional
3D	three dimensional
AASHTO	American Association of State Highway and Transportation Officials
AI	artificial intelligence
BIRM	Bridge Inspectors Reference Manual
BMS	bridge management system
CAD	computer aided design
CFR	Code of Federal Regulations
CG	center of gravity
COTS	commercial off-the-shelf
CMOS	complementary metal-oxide semiconductor
DEM	digital elevation model
DOT	department of transportation
DSM	digital surface model
DTM	digital terrain model
EO	electro-optical
FAA	Federal Aviation Administration
FC	Fracture critical
FHWA	Federal Highway Administration
FSDO	Flight Standards District Office
GB	gigabyte
GPR	ground penetrating radar
GPS	Global Positioning System
HD	high definition
IA	infrequent access
IR	infrared
LiDAR	light detection and ranging
LOS	line of sight
MnDOT	Minnesota Department of Transportation
MP	megapixel
MTU	Michigan Technology University
NBI	National Bridge Inventory
NBIS	National Bridge Inspection Standard
NTIA	National Telecommunications and Information Administration
ODOT	Oregon Department of Transportation
OJT	on-the-job training
RGB	red, green, blue
S-BRITE	Steel Bridge Research, Inspection, Training, and Engineering
SD	secure digital
TB	terabyte
UA	unmanned aircraft
UAS	unmanned aerial system
UBIT	under bridge inspection truck
VTOL	vertical takeoff and landing

CHAPTER 1. THE UAS DEFINED

Unmanned aerial systems (UAS) have been around nearly as long as manned aircraft, making their initial appearance during World War I, a mere 15 yr after the first powered flights at Kitty Hawk, NC. Until recently, UAS were largely used by governments and militaries. Large, remotely piloted, fixed-wing platforms provided intelligence, surveillance, and reconnaissance; target acquisition for military commanders and decision makers; and, in some cases, delivered weapons on those targets.

At present, those employing UAS to inspect bridges are using small unmanned systems. Given that most practitioners in the field refer to these systems as UAS regardless of their size or complexity, the term UAS is used in this report to cover all unmanned platforms used for bridge inspections.

Today, nearly anyone can buy and fly a UAS. Millions of these platforms are flown by hobbyists and in support of businesses, and new applications for UAS are being developed rapidly. Advances in materials and platform technologies, miniaturization of computer processors and sensors, decreases in system size and cost, and improvements in flight control systems have made this possible. As a result, UAS have become increasingly prolific, with innovators in many industries taking full advantage of their advancing degrees of technological sophistication and finding more and more uses for these platforms and the payloads they can carry.

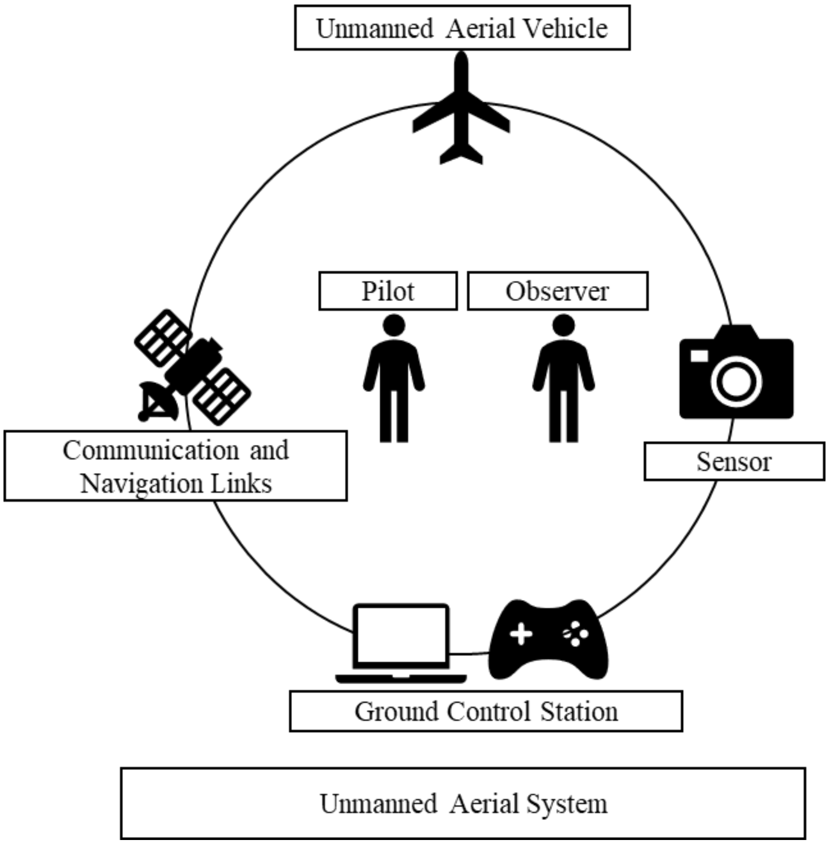
The Federal Aviation Administration (FAA) regulates all aircraft in the National Airspace System, including unmanned aircraft (UA). “Small Unmanned Aircraft Systems,” 14 Code of Federal Regulations (CFR) Part 107 of the Federal Aviation Regulations, is the current FAA regulation under which most UAS operate for commercial purposes (14 CFR 107 2016). These regulations govern UAS or unmanned platforms weighing less than 55 lb. At the time of publication of this study, approximately 100,000 certificated pilots were engaged in commercial applications of UAS in a growing number of industries, with the predominant application being aerial photography.

UAS are now used for firefighting in wilderness areas, search and rescue, agricultural management, construction stockpile management, wildlife monitoring, land surveys, and infrastructure assessments such as bridge inspections—the focus of this report.

WHAT IS A UAS?

The FAA defines a UA as an aircraft operated without the possibility of direct human intervention from within or on the aircraft. A UAS is the sum of all its components: the UA, also called the platform, the control station, the payload, and the pilot. The major components of a UAS are depicted in figure 1.

The control station provides the pilot a command and control link with the platform via radio frequency. A data uplink to the platform is used to control its movements, and a downlink from the platform may be used to provide telemetry, video, or other real-time data to the pilot. The payload is commonly an optical sensor, either electro-optical (EO) or infrared (IR); however, any number of optical or nonoptical sensors may be compatible with the platform. The pilot is the final and most important piece of the system, providing positive control inputs and flying the platform in a safe and professional manner. While not always a requirement, a visual observer can be employed as a part of the system to aid in scanning the sky to ensure flight safety is maintained at all times while the pilot concentrates on operating the platform.



Source: FHWA.

Figure 1. Graphic. Major components of a UAS.

WHAT UAS CAN DO

For bridge inspections, UAS can carry high-resolution cameras and other sensors near or into difficult-to-reach areas around and above the bridge. Parts of the bridge requiring visual inspection, an activity that traditionally requires placing people at risk to access the areas to be viewed, may be more easily reached using a UAS. Additionally, a UAS can reach challenging areas rapidly while producing live video that can be used by a certified bridge inspector in the field, allowing the user to capture photos of areas of interest or concern while the inspector remains in relative safety on the ground.

Following inspection flights, the data collected by a UAS can be processed to create multiple different products that can supplement inspection documentation, better inform decisionmakers regarding the structures, and improve future inspection planning.

WHAT UAS CANNOT DO

While UAS can provide several advantages to a bridge inspector, they currently cannot replace a person where tactile or other contact-inspection methods are needed or required. Additionally, UAS are restricted in their application by regulations issued by the FAA and other government agencies. These restrictions apply mainly to the airspace a UAS may use (e.g., locations near airports) and flight conditions that impact operation (e.g., night flying, adverse weather). These restrictions may or may not impact a bridge inspection. The flight restrictions on UAS users are revised as technologies improve and information on the practical use and safety of the systems is made available.

In no way should a UAS be considered a complete solution that will meet all bridge inspection needs. It is a tool that, when successfully employed by a qualified and proficient pilot in conjunction with a qualified bridge inspector, may bring increased efficiencies in terms of time and cost as well as improved safety for both inspection personnel and equipment.

KEY POINTS

When reading this report, a few key points should be kept in mind. First, *UAS technologies are changing at a rapid pace*. Platform flight controls, navigation methods, and payloads are advancing to the point that the state-of-the-art systems used in early UAS inspections a year or two ago might be obsolete today. At the time of this report, the primary types of payload usable in support of bridge inspections are imaging sensors. However, nonvisual payloads capable of performing inspection tasks beyond imaging are both in use as well as in development; however, such payloads are not fully vetted for use in bridge inspections at this time.

Secondly, in light of the current state of technology, when considering the practicality of integrating UAS into bridge inspection processes, the reader will be well served to simply think of a UAS as a “flying camera.” UAS do not radically alter the inspection process; rather, when used properly, UAS are tools that can simplify and possibly improve the inspection process. As the report discusses, a UAS can be used to capture photo imagery or live video of the bridge and bridge components with a resolution at least equivalent to that of a camera held by an inspector, whether the inspector is on the ground, in a boat, up close to the bridge structure, or in an aircraft flying above the bridge. With few exceptions, if photo documentation is needed for the inspection, a UAS can be used to get it. It should also be understood that use of a UAS does not remove or change any of the requirements for an inspection. All standards of a full bridge inspection still must be met by the inspector, including a properly written inspection report with proper narratives describing all deficiencies and assigning the correct National Bridge Inventory (NBI) codes and appropriate element condition states.

Lastly, this report describes noteworthy practices and recommendations based on field experiences and testing.[1] Nothing contained in it should be construed as a requirement. Organizations should modify the practices discussed to meet their requirements and standards.

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[1] This report contains background information, data, and unpublished project deliverables derived both from interviews and from research team members' hands-on experience working with departments of transportation in Colorado, Maine, Massachusetts, New Hampshire, and Vermont between July 2016 and the present.

CHAPTER 2. UAS AS AN INSPECTION TOOL

Bridge inspectors have a wide variety of tools available to meet the objectives of a bridge inspection in accordance with governing National Bridge Inspection Standards (NBIS). The fact that a UAS is an emerging technology should not dissuade inspectors from adding these systems to their inspection toolkits. The UAS currently available cannot conduct inspections requiring physical contact, but they can improve the inspection process in several ways.

A bridge inspection has three primary objectives (Wells and Lovelace 2018):

- Identify deficiencies and assess the current state of the bridge structure by employing a qualified inspector with the experience and expertise to identify conditions in need of attention.
- Document information through a written inspection report with photographs and sketches. The bridge owner uses these data to identify needs and to make management decisions regarding future operations, repairs, and maintenance.
- Provide recommendations for scheduling detailed, in-depth, follow-on inspections (if not needed for the current inspection); additional nondestructive testing; and load rating re-evaluation.

In many inspection scenarios, UAS can reduce or eliminate the need to have traditional inspection resources on-hand to meet these objectives. Some standard methods for accessing bridges, like using under bridge inspection trucks (UBIT), can be costly to operate and disrupt the efficient flow of traffic on the bridge. UAS can be a cost-effective solution for obtaining standalone, high-quality visual inspection data and can supplement standard inspection methods and equipment.

UAS can also enhance safety for the inspection team in many cases. Reducing inspectors' exposure to hazardous conditions presented by rough terrain, fast moving water, or severe heights is a key advantage UAS offer. UAS can also improve traffic safety for the public and for the inspection team (e.g., traffic-control personnel) by reducing the need for lane closures or the amount of time that lanes are closed.

Some UAS give inspectors the ability to examine areas that are difficult to access or in confined spaces, such as a closed spandrel arch. These areas present challenges or heightened risks to personnel. For example, during a 2018 study performed by the Minnesota Department of Transportation (MnDOT), contractors flying a collision-tolerant UAS captured imagery inside an enclosed steel arch (Wells and Lovelace 2018). Using this type of UAS inside the bridge structure removed the requirement for personnel to enter a potentially dangerous confined space—a procedure that requires specific training for the inspection team and entry permits in accordance with current safety regulations and practices.

BRIDGE INSPECTION METHODS

The ability of the UAS to augment or modify traditional inspection methods is a primary consideration when incorporating UAS into a bridge inspection program. Traditional inspection methods are both physical and visual and require access equipment suited for the bridge as well as additional tools to perform a complete inspection. Depending on the type, size, and condition of the bridge, the inspection team may need several different access methods and tools to complete the inspection, potentially at the cost thousands of dollars and hundreds of labor hours. Before discussing integration of UAS into inspection processes to meet bridge owner and inspector needs, a review of traditional methods, and how the use of a UAS can mesh with these methods, is of value.

Access Methods

Inspection teams use multiple access methods to conduct inspections and view critical components of the bridge. These methods include the following:

- Climbing/rope access.
- Aerial work platforms.
- UBIT/snooper.
- Ladder.
- Boat.
- Various lifts.
- Binoculars from the ground.

The access method used is dependent on the team, structure type, and conditions. No matter the method used, each one presents a specific monetary cost; a safety consideration or risk; time requirements for set-up, use, and removal; and, in some cases, advanced training.

UAS can access most places an inspector would need to go and, in some cases, areas that the inspector cannot readily reach or is restricted from entering due to unsafe conditions. Collision-tolerant UAS, which are platforms with collision guards (e.g., enclosed within a protective cage) or obstacle-detection sensors, can be flown in close contact with the surface on the underside of a bridge and adjacent to girders. Very small systems may also be flown into tight areas where two bridge elements come together. Additionally, zoom capabilities can allow the sensor to produce results that mirror those of a platform being very near or in contact with the structure using UAS equipped with a protective cage.

In addition to accessing the bridge structure, UAS can fly to areas away from the bridge to get a general view of the bridge site. UAS, both rotary and fixed-wing systems, can be used to conduct mapping of the roadway approaches and upstream and downstream channels to observe changes in stream stability alignment causing conditions detrimental to the life of the structure.

INSPECTION TOOLS

The *Bridge Inspectors Reference Manual* (BIRM) lists seven tool categories used during bridge inspections (Ryan et al. 2012):

- Inspection.
- Cleaning.
- Visual.

- Measuring.
- Documentation.
- Access.
- Miscellaneous Equipment.

Most tools available to inspectors in these categories cannot be currently carried by a UAS to perform a physical inspection or would be unusable or impractical until a remotely actuated equivalent is developed.

Of the seven inspection tool categories, four are currently used (or projected for use) in conjunction with a UAS-assisted routine visual inspection: visual, measuring (estimates from images after postprocessing), documentation, and bridge access.

NONDESTRUCTIVE EXAMINATION

In the future, UAS may be capable of performing or supporting bridge inspections where nondestructive examination (NDE) tools and techniques are used to detect defects and deficiencies in a material without causing damage to the structure. NDE techniques are used by the inspection team to identify structure movement, corrosion, fatigue cracking, and delamination. To identify these defects, NDE tools are employed to sound and evaluate bridge elements from within arm's reach or closer. The inspector will sometimes employ ultrasonic testing to measure steel section loss or use dye penetrants and magnetic particle testing to evaluate fatigue cracking in steel elements. Table 1 shows a list of NDE devices and the defects detected in bridge elements by each.

Table 1. NDE tool inspection uses.

Bridge Element	Defect	NDE Tools
Concrete deck	Delamination/rebar corrosion	Hammer sounding, chain sounding, ground penetrating radar (GPR), impact echo, infrared thermography
Pins/hangers/eye bars	Fatigue cracks	Ultrasonic
Steel girders/trusses	Fatigue cracks	Eddy current, ultrasonic, IR, radiography, acoustic emissions
Concrete prestressed girders	Strand corrosion	Magnetic flux leakage, strain gauges
Concrete posttensioned girders	Corrosion, grout voids	Impact/ultrasonic echo, GPR
Bearings	Movement, lack of movement	Tilt meters, remote sensor bearings
Concrete columns	Rebar corrosion	Hammer sounding, GPR, ultrasonic pulse velocity
Foundations	Integrity and scour	GPR, sonar, crosshole sonic logging, time domain reflectometry, parallel seismic

Apart from ground penetrating radar (GPR) and IR, UAS payloads are not currently available to meet these inspection needs. Technologies that may provide some of these capabilities (e.g., ultrasonic and eddy current sensors) via UAS in the future are in development. UAS technology advances on the horizon are discussed further in chapter 8.

IDENTIFYING WHERE UAS WORK BEST

Bridge owners in some early UAS adopter States have compiled a list of bridges where supplementing routine inspections with UAS is recommended. Typically, the bridges on such a list present challenges to gaining access to all parts of the structure for a comprehensive inspection. For example, an excessively wide bridge requiring a UBIT where access is only possible from one side of the bridge could be a good candidate for inspection augmentation with a UAS. In such a case, what can easily be seen on one side of the bridge may not be visible on the opposite side of the structure due to the reach limitations of the UBIT. A UAS could provide imagery from one side of the bridge while the UBIT is used in an optimal manner on the other side. If defects are found using the UAS, the bridge owner will need to access the site physically to determine the extent and severity of defects.

It may also be useful to identify which aspects of a bridge inspection are best suited for UAS use according to the individual needs of the organization. The Oregon Department of Transportation (ODOT) identified major bridge reporting categories and applied a scale of 1 to 4 (1 = not useful, 2 = limited use, 3 = useful, and 4 = very useful) to rate the usefulness of a UAS for providing inspection information. ODOT also evaluated how useful a UAS is in conducting various types of inspections. An example of UAS usefulness ratings are depicted in table 2 (Gillins et al. 2018). It is notable that the early evaluations by ODOT determined that UAS were useful or very useful in most reporting categories and inspection types.

Table 2. UAS usefulness by reporting category and inspection type (Gillins et al. 2018).

Category	Item Type	Usefulness Rating
Inventory	Geometric data	4
	Structure type and inventory	3
	Navigation data	3
	Age and service	2
	Proposed improvements	2
	Identification	1
	Classification	1
	Load rating and posting	1
	Inspections	1
Appraisal	Structural evaluation	4
	Deck geometry	4
	Underclearances	4
	Approach and road alignment	4
	Waterway adequacy	3
	Traffic safety features	3
	Scour critical bridges	2
Inspection	Initial routine	4
	Routine	4
	Damage	2
	Indepth	2
	Fracture critical	2
	Underwater	1
	Special inspections	1–4
Condition	Deck	4
	Superstructure	4
	Substructure	4
	Channel and channel protection	3
	Culvert	3

DEFECT FINDINGS IN STATE-SPONSORED REPORTS

A growing number of State departments of transportation (DOTs) have conducted research or implemented programs employing UAS and their sensors for bridge inspection purposes. These efforts have had success identifying bridge defects and in collecting information important to the bridge inspection planning process. Imagery captured during bridge inspections can be used for creating accurate two dimensional (2D) and three dimensional (3D) models of a bridge that are usable for various analytical and planning purposes.

Table 3 summarizes some of the types of bridge defects inspectors from several States were able to detect using UAS. In these instances, UAS enhanced the inspection process or improved the accuracy of results. The table represents a sample of the defects found in the studies researched for this report and should not be interpreted to mean that these are the only defects that can be detected using a UAS-mounted sensor. Links to the individual reports detailing these UAS capabilities can be found in appendix C.

Table 3. Summary of detectable bridge defects discovered utilizing UAS imagery.

Defect	Florida[1]	Idaho	Minnesota[3]	Michigan[4]	Oregon[5]
Concrete cracks	✓	✓	✓	✕	✓
Missing fasteners	✓	✕	✓	✕	✓
Rust	✓	✓	✕	✕	✓
Peeling paint	✕	✕	✕	✕	✓
Delamination (using IR sensor)	✓	✓[2]	✓	✓	✕
Spalling	✓	✕	✓	✓	✓
Stress cracks (wood)	✓	✕	✕	✕	✕
Vegetation/debris	✓	✓	✕	✕	✓
Efflorescence	✓	✓	✕	✕	✓
Corrosion	✓	✓	✓	✕	✕
Concrete wear	✓	✕	✕	✓	✕
Fatigue crack (weld)	✕	✓	✕	✕	✕
Paint condition	✓	✓	✕	✕	✓
Galvanizing condition	✕	✕	✓	✕	✕
Previous repairs	✓	✕	✓	✓	✓

✓ = detectable ✕ = undetectable.

[1] This column lists the results of two studies conducted in Florida in 2015 and in 2018 (Otero, Gagliardo, and Cosentino 2015; Bridge, Ifju, and Tomiczek 2018).

[2] The delamination the Idaho team identified was also simulated in lab conditions (Dorafshan and Maguire 2018). Note: Detection of delamination of bridge decks using UAS is also being tested by the Utah DOT.

[3] The Minnesota results are from a three-phase study that was conducted from 2015 to 2018 (Zink and Lovelace 2015; Wells and Lovelace 2017, 2018).

[4] Brooks et al. 2015.

[5] Gillins et al. 2018.

CHAPTER 3. UAS SENSORS

This chapter discusses features and characteristics of different sensor types, including camera lenses, which are typically measured in metric units (i.e., millimeters). For reader convenience, 1 mm = 0.04 inches.

The visual sensor is the primary payload carried by a UAS to support bridge inspections. While the platform and its performance capabilities can provide access to difficult-to-reach parts of a bridge, it is the sensor that captures imagery and data that allows inspection teams to perform their job for the bridge owner. Because it is such an important element of the system, the sensor selected for a particular task must be capable of collecting the types of information at the level of quality required to meet inspection standards. Understanding a sensor's inherent capabilities and characteristics and the information each type of sensor provides will enable an inspection team leader to advise the bridge owner on the best sensor or sensors to meet their needs.

THE SENSOR MARKET

Sensors capable of being mounted and carried aboard a UAS can generally be classified into three categories: consumer grade, professional grade, and commercial grade. While these categories are not industry-standard terms, they are defined in this report to provide clarity for the reader when reviewing different sensor capabilities and to assist in determining the effort necessary to train personnel to a level of basic proficiency.

Consumer-grade sensors are integrated into the flying platform, are readily available to the public, and require little to no formal training to employ effectively. The quality of the images produced varies; however, in some environments and in certain scenarios, a consumer-grade sensor may be preferable to a more complex and expensive sensor. Sensors in this category are typically EO cameras providing up to 4K video,[2] as well as a 12 to 20 megapixel (MP) photo capability.

Professional-grade sensors are capable of providing adequate levels of detail and may be preferable for bridge inspection use. Some of these sensors can provide images from bands of the electromagnetic spectrum outside of visible light. These sensors typically require specialized training and a more advanced level of experience to be employed efficiently and produce the image quality needed to meet bridge inspection needs. These sensors will have 4K video and 20 MP or greater photographic capabilities. IR sensors are included in this category.

Commercial-grade sensors include light detection and ranging (LiDAR) systems, multispectral cameras, and hyperspectral imagers. These systems require a significant level of training and experience to be used as an effective bridge inspection tool. Training for commercial sensors may be offered by the sensor manufacturer and is often provided as part of the purchase contract. Users of these advanced sensors have also received training from third-party vendors and UAS operators with developed training programs.

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[2] The term 4K refers to the number of horizontal pixels in an image (or on a screen) and comes in two standard sizes: 3,840 by 2,160 pixels or 4,096 by 2,160 pixels.

In addition to understanding sensor capabilities and characteristics, it can be helpful to view the sensor categories by when it is preferable to opt for one over another. Consumer-grade sensors may be preferable when the task presents a high risk of asset loss—a consideration purely based on the cost to acquire a new system. Professional-grade sensors can also be used for higher risk applications and are suited for specific defect detection techniques, such as IR inspection of concrete, but it is advisable that the UAS have an indoor navigation system to aid in platform stability for operations conducted close to the structure. Finally, commercial-grade sensors, generally the most costly, are more suited to applications where very specific and refined information is needed. However, nothing stated here should be construed to mean that use of any of these sensors is limited to just one specific scenario or application. Each can be equally effective when employed according to safe, standardized operating procedures and when, in the hands of a skilled pilot, the risk of system damage or loss is greatly reduced.

Table 4 compares each of the three categories of sensor that may be used for bridge and infrastructure inspections. The table gives a comparison of sensor types currently known to be used during bridge inspections according to the sensor grade categories: EO cameras, IR cameras, and LiDAR systems. It illustrates a variety of options and capabilities available to the inspection team.

Table 4. Sensor comparison chart.

Specification	Consumer		Professional				Commercial	
Type of sensor	High-resolution EO	High-resolution EO	High-resolution EO	High-resolution EO	High-resolution EO	IR	IR	LiDAR
Resolution	12.4 MP	16 MP and 4K	20 MP and 4K	20.2 MP	24 MP	640 × 512 13mm	640 × 512 IR 1920 × 1080 EO	100k shots/s
Cost	$459	$2,200	$1,500	$650	$2,699	$1,900	$11K	>$100K
Power required	Not available	Not available	15.2 V Lithium-ion battery	3.6 V, 1240 mAh battery	Not available	15.2 V Lithium-ion battery	Not available	80 W
Weight	262 g	526 g	>1 lb	>1 lb	449 g	>1 lb	450 g	>8 lb
Software requirements	Manufacturer operating system	Manufacturer operating system	Manufacturer operating system	Varies	Manufacturer operating system	Manufacturer operating system	Manufacturer operating system	Manufacturer operating system
Possible inspection application	Inventory	Inventory	Inventory, defect localizing/ assessment	Inventory, defect localizing/ assessment	Inventory, defect localizing/ assessment	Inventory, defect localizing/ assessment	Inventory, defect localizing/ assessment	Mapping
Product output	MP4/MOV, JPEG, DNG, JPEG+DNG	DNG, RAW, JPEG, MOV, MP4	DNG, RAW, JPEG, MOV, MP4	RAW, JPEG	Cinema DNG, ProRes MP4/MOV, JPEG, DNG, JPEG+DNG	DNG, RAW, JPEG, MOV, MP4	Radiometric JPEG, RAW, JPEG, MOV, MP4	DNG, RAW, JPEG, MOV, MP4
Level of training required (operator)	Minimal moderate	Minimal moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Significant

Note: MP4, JPEG, DNG, RAW, and MOV are media files.

There can be a significant amount of capability crossover between the sensor categories. The key for bridge inspectors is to select the sensor type and grade that is capable of producing the imagery quality required for the final inspection products.

The UAS sensor market can be further divided into two primary manufacturing bases: commercial-off-the-shelf (COTS) sensors and custom sensors. COTS sensors are sold to the general public and can be easily purchased online or through local retailers. COTS sensors range in price from a few hundred dollars for the simplest systems to a few thousand dollars for multisensor systems. The more advanced the sensor, the higher the cost. As examples, a COTS EO camera may cost less than $500, whereas a COTS LiDAR sensor may cost in excess of $100,000.

Custom sensors are the most advanced and generally the most expensive. These are sensors that are produced or modified to meet specific requirements or needs. Custom sensors may rely on core parts from COTS manufacturers or may be entirely manufactured with proprietary processes and components. These sensors can be an integral component of UAS, or they can be mounted on an interchangeable ball turret or removable three-axis, stabilized gimbal. The sensors produced by custom manufacturers can cost significantly more than commercial sensors and are generally manufactured to suit a custom platform or specific task.

SENSOR TYPES

EO sensors capture reflected light from the visible light spectrum, convert it to an electronic signal, and store it as an image (Woodford 2018). A digital camera is an example of an EO sensor combined with an optical lens system. These types of sensors are often referred to as "RGB" sensors, or cameras, because they capture images in the red, green, and blue frequency bands. Modern, high-resolution EO cameras allow users to capture very detailed imagery that may have applicability for a variety of purposes in bridge inspections. Examples of the level of image detail, along with examples of their uses, are shown in the figures that follow.

Figure 2 shows an EO image of a bridge deck taken from well above the bridge itself. The image shows areas of irregularity on the bridge deck and the image quality is sufficient to enlarge areas of interest.

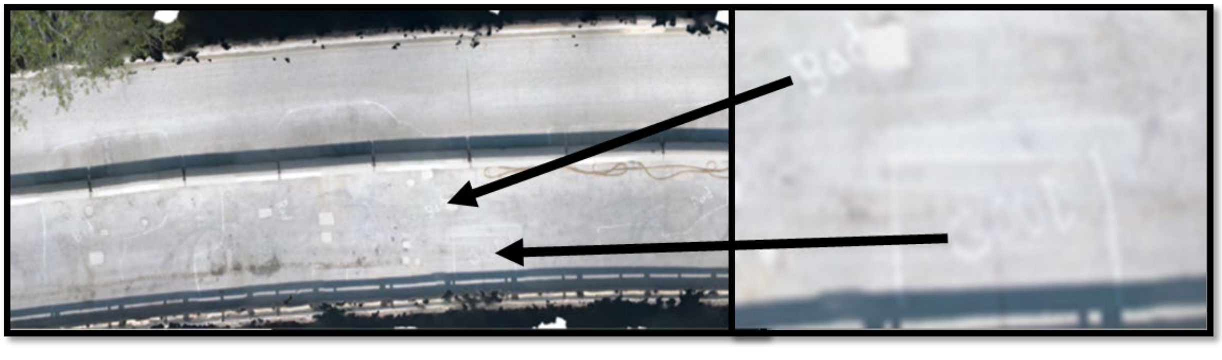

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Figure 2. Photo. Example digital camera sensor image of a bridge deck.

A series of images can be combined to form a mosaic, create maps, or develop a 3D model. In figure 3, a combination of orthorectified images, or images that have a consistent scale and where features are presented in their true positions, was used to craft an orthophoto of a bridge deck.

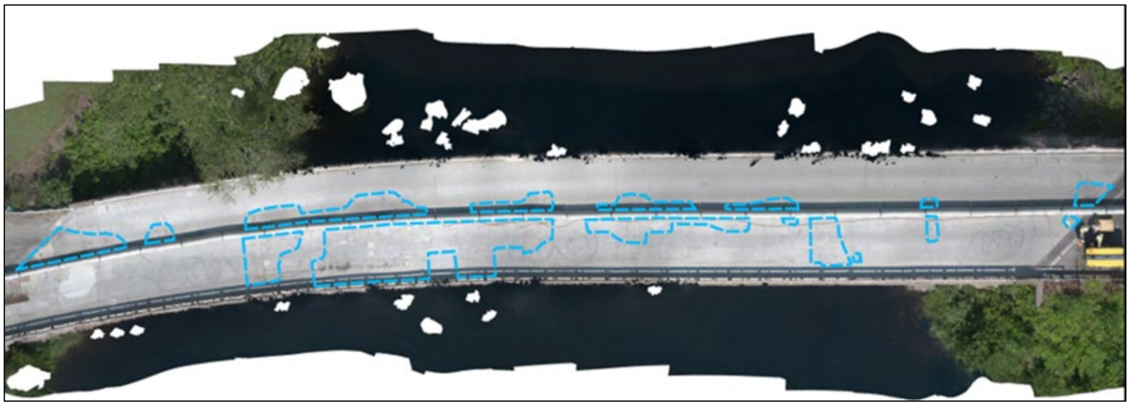

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Figure 3. Photo. Example of a digital camera sensor orthorectified image of a bridge deck.

Collections of EO images are also used to build electronic models of formations or structures using a technique known as photogrammetry. This technique can be useful for developing 3D models for spatially cataloging images. This technique is discussed in greater detail in chapter 7.

When coupled with a variable zoom lens, the high-resolution sensors allow inspectors to get more detailed shots without physically maneuvering the platform closer to the structure. This capability reduces the requirement for an inspection team member to compromise personal safety to gain access and observe an area of the bridge that does not need to be physically touched to accomplish an inspection task. Keep in mind that the quality of zoomed-in imagery may be degraded when compared with imagery captured without zoom.

IR sensors measure thermal energy radiation. IR radiation is a form of electromagnetic radiation with wavelengths much longer than those in the visible spectrum. The human eye cannot see thermal radiation, but these sensors take thermal energy and convert it to an electric signal that can then be visualized in an image using colors in the visible spectrum. All objects above absolute zero in temperature emit thermal radiation, and IR cameras are tuned to detect this radiation in specific frequencies and ranges. With knowledge of the image subject material, location, and environmental conditions, a trained thermographer can extract temperature data from a thermal image.

The ability of the IR sensor to detect variances in thermal radiation on surfaces make it effective in identifying potential degradation in the structural materials used in bridge construction (e.g., identifying delamination of a concrete bridge deck). This technique can potentially eliminate or reduce the need to perform time-consuming conventional materials tests and can provide information valuable in determining where to focus physical or mechanical inspection and testing.

Defect detection is achieved by using the IR sensor to identify thermal variations on the surface caused by uneven heating or cooling that results from imperfections or anomalies in the materials (Vaghefi et al. 2011). For example, if a delamination or gap is produced below the surface, it will cause a thermal discontinuity. When the bridge is under heating or cooling conditions, these discontinuities cause the surface above the gap to heat or cool at a different rate. These differences are then detectable by the IR sensor.

An example of an IR image that identifies bridge-deck delamination is shown in figure 4. The areas outlined in light blue dotted lines depict delaminated areas of unsound concrete located using traditional hand sounding and mapping. These traditional methods can be time consuming and disruptive to traffic. The yellow and orange areas highlighted using the IR imaging technology correspond well to the areas of interest identified using traditional mapping techniques. The bridge in this image is an active construction project. The dark areas in the center of the image are the result of the barriers placed by the construction team to divide the traffic lanes, creating shadows, and the other dark areas are deck patches on areas recently repaired by the contractor.

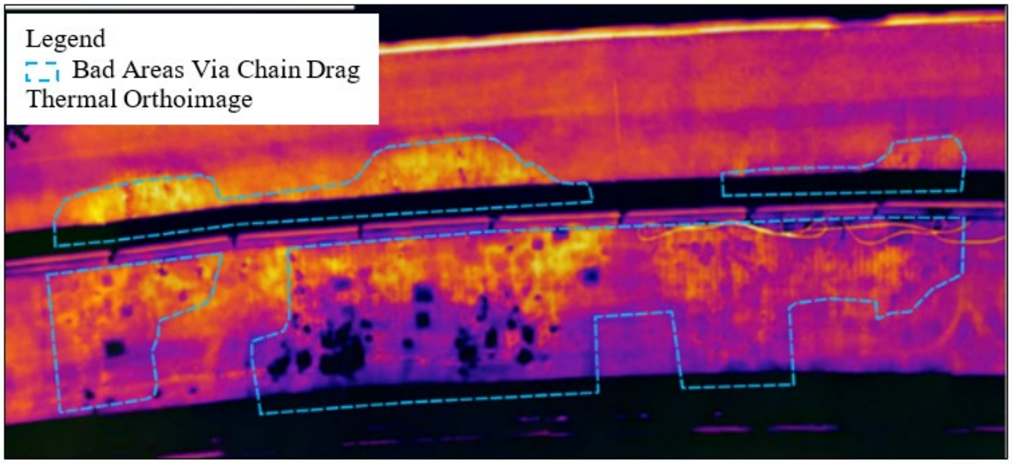

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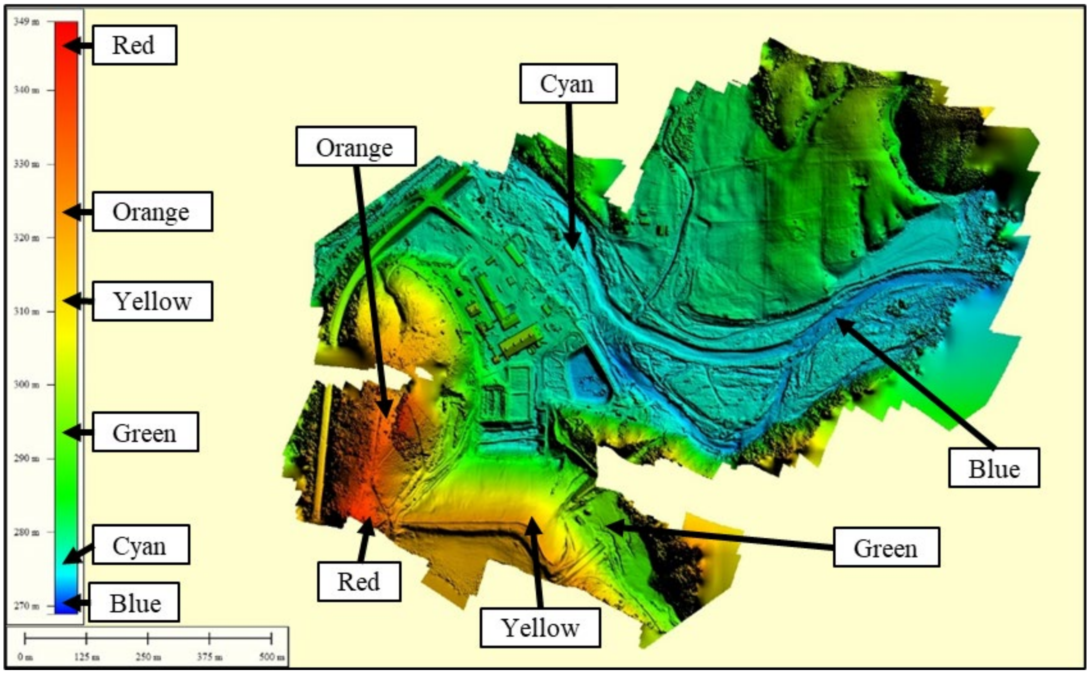
Figure 4. Photo. Example of an IR image (shown in "ironbow" palette) of possible bridge-deck delamination.

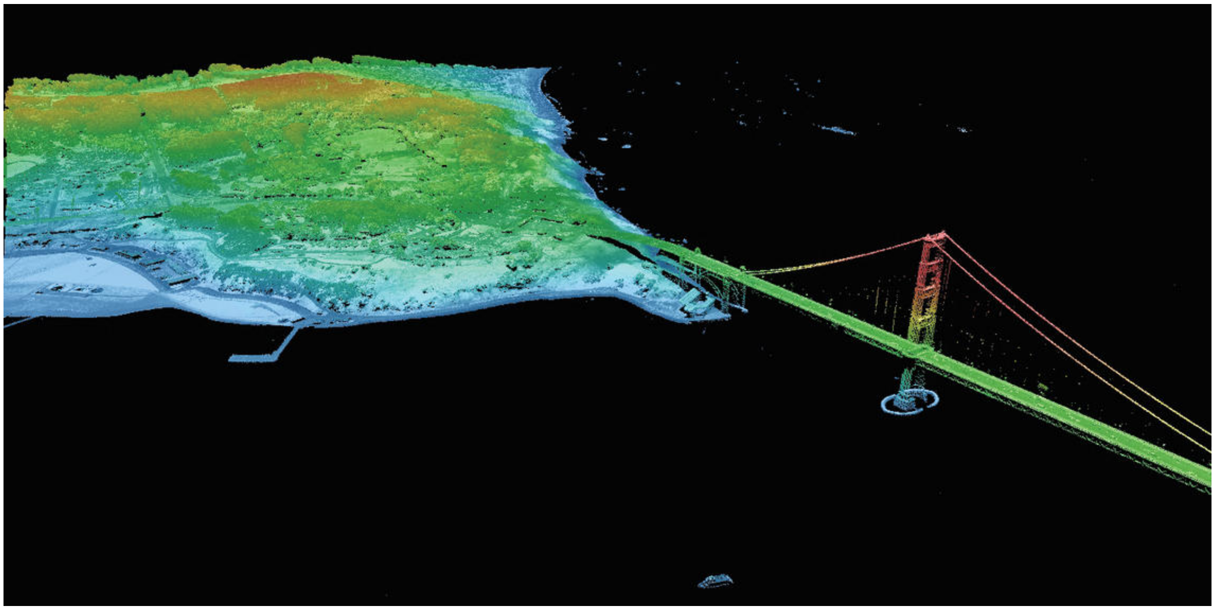
Good correlation between thermal imaging and traditional inspection techniques was found in the top traffic lane, which was subjected to consistent heating conditions; however, the bottom lane was covered intermittently by ground crews and vehicles, skewing the results. This outcome exemplifies the importance of thermography training for interpreting the captured images and knowing the environmental conditions leading up to image capture.

Unlike EO and IR cameras, which passively respond to inputs from the environment, LiDAR sensors actively emit pulses of light, up to hundreds of thousands of returns per second, to measure the distance between the sensor and a target object accurately. This measurement is achieved by calculating the time it takes for a pulse to hit a target and return to the sensor (USGS n.d.). The information can then be either used during the postprocessing phase to create 3D point-cloud models or processed further in digital elevation models (DEMs), as shown in figure 5. A LiDAR point cloud of a bridge is depicted in figure 6.



Source: USGS.

Figure 5. Photo. Example of a DEM depicting elevations in varying colors.



Source: USGS.

Figure 6. Photo. Example of a LiDAR point cloud of the San Francisco Bay and the Golden Gate Bridge.

A LiDAR system consists of three main components: a global navigation satellite system for determining the LiDAR system's location, a laser scanner for sending and receiving signals, and an inertial navigation system for measuring the three-axis (6 degrees of freedom) attitude of the system (USGS n.d.). The combination of precise navigation and laser measurements result in extremely accurate results (i.e., within millimeters) when properly calibrated. UAS-based LiDAR systems vary in accuracy and precision. These systems provide accuracy comparable to that of high-end photogrammetry on hard surfaces when conducted properly. The main advantages of LiDAR over photogrammetry are the ability to penetrate vegetation with multiple returns, faster imagery processing times, and improved capabilities to resolve fine features.

SENSOR INFORMATION PRODUCTS

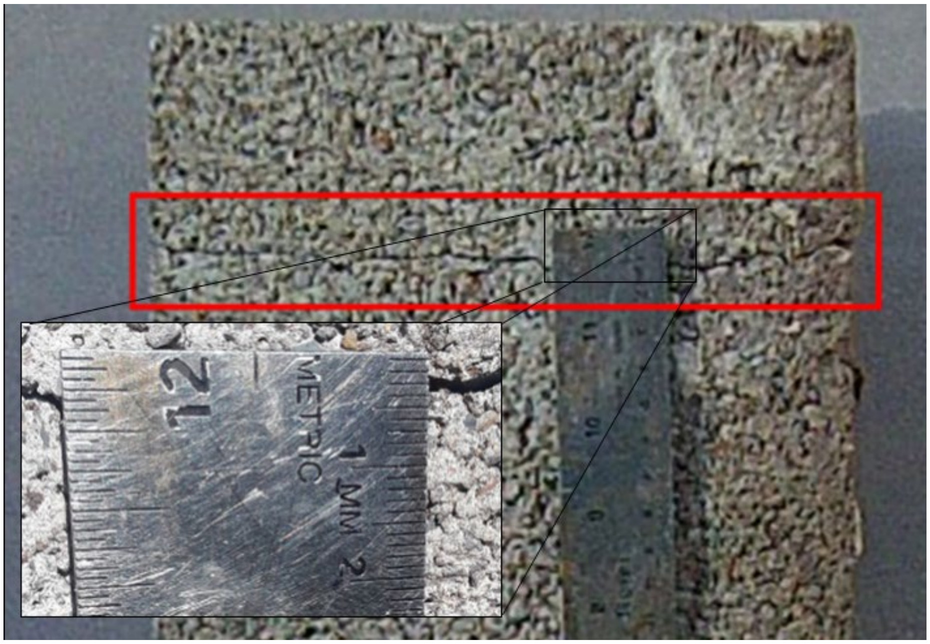
Postflight imagery and data processing, typically referred to simply as postprocessing, takes the raw data captured by the UAS payload sensor(s) and transforms it into actionable information for bridge inspectors, engineers, and owners to use to satisfy inspection requirements. Common UAS sensor information products include images, video, orthophotos, orthomosaics, 3D models, and surface models.

Images

High-resolution EO images allow the inspector to see deficiencies in an “up-close” or magnified manner without having to physically access the specific area on the bridge. UAS captured EO images may reveal defects missed using routine visual inspection techniques applied from a distance. High-resolution imagery can be used to create a record of surface defects and allow visual comparisons with previous inspection images to track defect deterioration or propagation over time. High-resolution EO images are the most often captured and used UAS imagery products for bridge inspections.

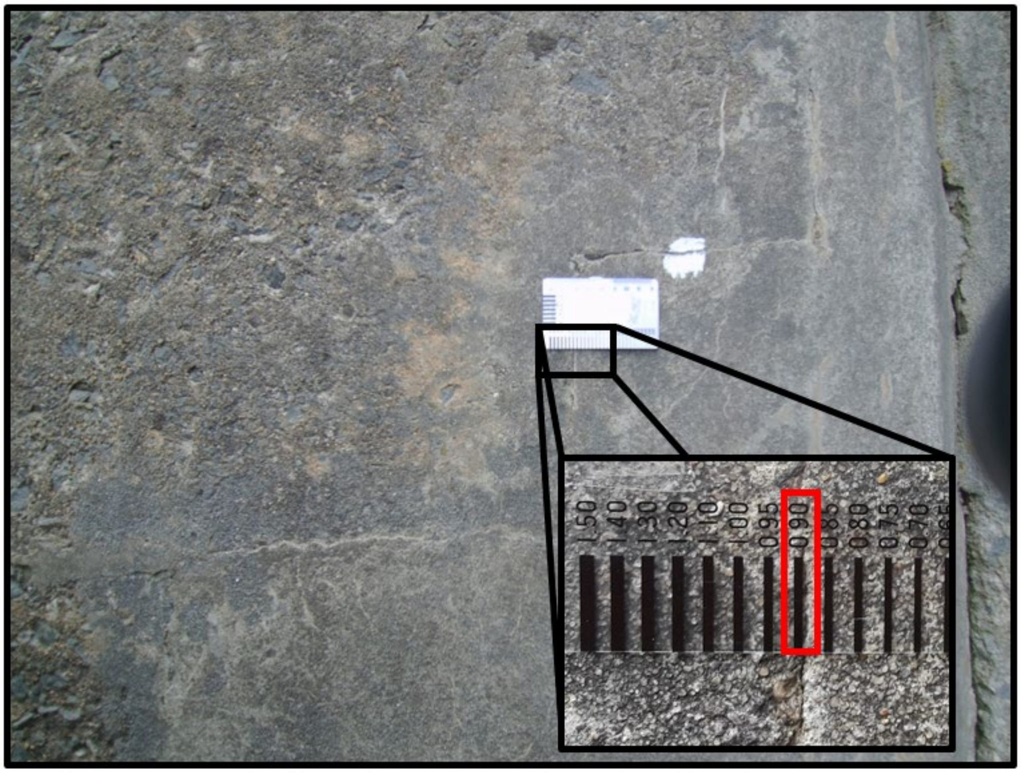
Figure 7 is an example of an image product from a COTS professional-grade EO camera. It depicts a concrete block with a crack running through the short axis (within the red box). It was taken using a 12.4 MP camera with a 14-mm lens and an aperture setting of F2.8 from 36 inches (0.91 m). The original image is 5.75 by 7 inches (14.6 by 17.8 cm). The image was not put through any postprocessing beyond cropping the original image to frame the subject. The embedded close-up was an additional image taken from approximately 6 inches away from the block to highlight the size of the crack, with a millimeter-incremented ruler, and to illustrate the resolution and detail these sensors can offer. While placing a UAS sensor within 6 inches (15.24 mm) of a bridge component is not safely feasible, this example provides an idea of the product that even a low-resolution sensor can offer the user.

Figure 8 presents another example of an EO image, this one taken in the field of a bridge component and utilizing a crack comparator card. The figure depicts a small crack on a patch of a concrete wing wall that appears as a thin white line at the bottom left of the comparator card. The crack is approximately 0.035 inches (0.90 mm) in width as measured by a crack comparator card overlaid. The image was taken using the same camera as figure 7 with the UAS camera hovering approximately 36 inches (0.914 m) away from the structure. No postprocessing was done to the image other than reducing the original 13- by 10-inch (33 by 25.4 cm) image to fit the page. The image was captured under ambient light conditions during the afternoon at the bridge location. The embedded close-up image was an additional image taken with a 13 MP handheld camera from approximately 6 inches (15.240 mm) away so that the measurements on the crack comparator could be seen for reference.



Source: FHWA.

Figure 7. Photo. Professional grade COTS EO image.



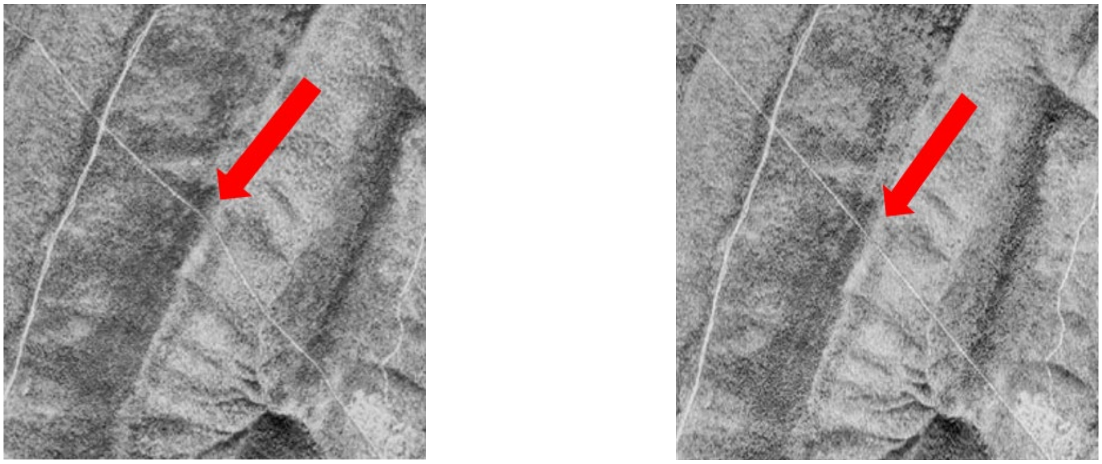
Source: FHWA.

Figure 8. Photo. EO image with crack comparator.

Orthophotos

High-resolution images from IR and EO cameras can be used to create orthophotos—images that have the depicted geometry corrected, or orthorectified. Orthophotos can be used to extract true measurements from the depicted structure or terrain and thus serve as a base map for other overlays used for planning (USGS 2016). Orthorectified imagery can also be input into computer-aided design (CAD) programs to help model member dimensions.

Figure 8 depicts an example of the benefits of an orthophoto. In postprocessing, the scale of the image is uniformly corrected so that it is an accurate representation of a surface and can be used to extract measurements like any other map, making these images useful for construction and inspection planning, postdisaster evaluation, and other such measurements the bridge owner may require. In figure 9-A, the red arrow points to an area that has not been rectified. One can see the waviness in the line (a power line right-of-way in this case), which would make accurate measurements of the feature very difficult to attain. In figure 9-B, the red arrow is pointing to the same physical feature after the image has been rectified. The noticeable difference is that the curvature in the line has been removed, making extracting measurements easier and more accurate.



Source: USGS.

A. Before orthorectification.

Source: USGS.

B. After orthorectification.

Figure 9. Photo. Before and after orthorectification.

Orthomosaics

An orthomosaic is an accurate representation of an area that has been created by stitching together many orthorectified images. Typically, this is done using photogrammetry software that uses “tie points” appearing in multiple images to connect those images. The software can use a combination of manually and automatically generated tie points. In the simplest terms, the end result is a single, much larger orthorectified image.

3D Models

UAS give the bridge owner the ability to capture images of an entire bridge structure from vantage points not previously available using EO or IR cameras. This capability facilitates the creation of computer models of the bridge using photogrammetric techniques and LiDAR. 3D models allow the inspector and the bridge owner to view structures from different perspectives and angles, better understand the overall geometry of the bridge in a spatially accurate format, and represent the location of the defect visually after the inspection. They also provide a very effective visual means of presenting the information to multiple stakeholders.

Surface Models

Digital surface models (DSMs), digital terrain models (DTMs), and DEMs can be produced using photogrammetry techniques and with LiDAR. While these three types of models are similar, they each have distinct characteristics. A DSM includes all features scanned, both natural and synthetic. A DEM is a 3D raster model that has all vegetation and structures removed. A DTM is very similar to a DEM except that it is typically a vector file with additional terrain features added, such as contours or break lines. Such models can assist bridge owners in hydrological assessments and erosion monitoring around the bridge. They can also be used as a visual tool for depicting the entire bridge structure, similar to the 3D point cloud.

Video

UAS sensors can provide the inspector and bridge owner with a mobile source of high-definition (HD) video. The video is streamed in real time from the platform and can be recorded to support a range of inspection needs. Video can be used to provide real-time viewing of the inspection, either on location or from remote stations, and HD video can also provide a source from which photos may be extracted. Such images can be found and viewed after the flight to create inspection products during the postprocessing phase of the inspection.

The detection of bridge defects using video from a UAS can occur in real time or during postprocessing of UAS inspection data, depending upon the size of the defect. Researchers supporting the Florida DOT were able to detect the minimum reportable crack of 0.004 inches (.01 cm), per American Association of State Highway and Transportations Officials (AASHTO) guidance, at 4 ft from the surface being inspected using a COTS EO camera with 1080p video. However, a crack this size could only be detected during postprocessing; the images transmitted in real time only provided a high enough resolution to clearly see cracks that were 0.06 inches (0.16 cm) or larger (Otero, Gagliardo, and Cosentino 2015).

Product Output

For most UAS, the imagery and data captured during a flight are stored on a removable media storage device integrated into the platform, such as a secure digital memory (SD) card. The files are stored using a variety of common file types that can be accessed by media viewing and postprocessing software. Some common types of image-file formats are JPEG and DNG for photos, and MOV and MP4 for videos. Other file formats are also used by currently available sensors, and the format the sensor uses to store data may impact the choice of postprocessing software to be used.

It may be necessary to keep multiple removable media-storage devices on hand due to the sheer volume of information that can be collected during a single flight.

SENSOR CHARACTERISTICS

Numerous manufacturers produce various models of UAS sensors that can be used for bridge and infrastructure inspections. The fact that sensors and platform are in a constant cycle of development and improvement can be intimidating and make it difficult to identify the correct sensor to use for a specific job. It can also be a time-consuming task with costly results if the wrong sensor is selected.

The factors influencing sensor choice are dependent upon the capabilities needed, what the user can afford, and which sensor characteristics will be most critical to accomplishing desired tasks.

The following is a list of sensor characteristics that UAS service providers have found beneficial when performing bridge inspections:

- *Availability*. While acquiring a custom sensor may provide superior inspection results, it may also delay replacement if it is damaged or destroyed during an inspection. A more readily available sensor may be a better option if multiple inspections are to be performed in a short timeframe.

- *Data Storage*. Data captured by sensors may require a large storage capacity (i.e., terabytes), either internal to the platform or sensor or at the ground control station.

- *Downlink Capabilities*. Robust downlink capabilities allow for live data feeds to the system controller, the inspector, or both to ensure the quality of the data and images is satisfactory.

- *Ease of Interchangeability*. The ability to change sensors (or lenses) rapidly reduces total downtime between flights and thereby reduces inspection costs.

- *Georeferencing Capability*. This sensor capability aids in image identification and location accuracy during postprocessing.

- *Lighting*. Self-contained lighting systems provide increased image quality when operating in confined environments (e.g., under a bridge deck). Lighting systems also improve safety when operating in low-light conditions.

- *Ruggedness*. The ability of the sensor to continue to operate in adverse conditions and contact, including adverse weather conditions, is a plus for inspections.

- *Size and Weight*. The larger and heavier the sensor, the greater the adverse effect on the overall performance of the platform, such as reducing the platform’s total available flight time on a single battery charge. Larger payloads require a larger platform, which may be more difficult to maneuver in confined spaces.

- *Cost*. The system must be economically viable and provide a good return on investment. Lower-cost systems make scaling a UAS program more affordable.

Apart from these sensor characteristics, additional considerations should go into the selection of the sensor that is best suited to accomplishing inspection tasks. The following list details some key selection considerations:

- *Budget*. Developing an internal budget will provide a baseline criterion for the grade and type of sensor that can be acquired. Budget considerations should consider the sensor's lifecycle and the rate at which the technology becomes obsolete.

- *Data and Information Requirements*. Understanding exactly what information is required to satisfactorily complete an inspection and having an estimate of how much data may be captured during a single inspection will inform the user on the sensor quality and capabilities needed.

- *Experience Requirements*. Does the sensor need an experienced operator to provide quality data? The level of operator experience can directly and proportionately affect the quality of the information that is gathered, with some systems benefitting more from the experience level of the operator than others.

- *Specific Tasking*. No single sensor can perform every task. Identifying the tasks and selectively matching the sensor capability to specific tasks may enhance the results.

- *Technology Obsolescence*. UAS technology is advancing at a very rapid pace; however, these advances do not mean that a sensor will be unable to produce quality data 2 yr in the future. It is more likely that the age of the system will impact the manufacturer's ability to provide maintenance on a malfunctioning sensor, perhaps due to the manufacturer discontinuing software updates or stopping sensor or platform production. Ensuring that both the acquired platform and the sensor are not more than a year or two old and are produced by a manufacturer with a reputation for supporting their products for several years after production stops may minimize the risk of needing to fully replace a system before the end of its estimated lifecycle.

- *Training Requirements*. How personnel will be trained to operate the sensor will impact how well the sensor is employed. Several types of training are available to teach personnel about sensor operation, from on-the-job training (OJT) to formal instruction. Each method has its benefits and drawbacks that need to be evaluated. The training selected should be commensurate with the level of sensor complexity and the required tasks. For example, OJT for a consumer-grade sensor integrated into the UAS may be adequate for general use and overhead imagery, but more extensive training may be necessary to capture quality images under the bridge structure.

Sensor Image Quality

The quality of the image the sensor captures is an important factor when selecting a system for bridge inspections. When referencing a camera sensor, it is common to hear resolution talked about in terms of MP. The number of MP that a camera has and what the MP count does for the final product can cause confusion. Simply stated, the higher the MP count, the greater the level of detail in each image. The higher the MP count, the more of the image can be digitally magnified or blown up without losing fidelity.

Not all cameras are manufactured to the same standard, and the sensor MP count is just one factor contributing to image quality. Sensor size and lens quality also play important roles. A small sensor coupled with a low-quality lens may produce lower-quality images even with a high MP count. Conversely, in some situations it is possible to have a lower MP-count camera outperform other systems if a high-quality lens is used and the sensor is physically larger.

Most digital-camera sensors today advertise high resolution as a selling point. Most EO camera sensors can capture 4K video and photos in excess of 24 MP. By reference, 4K video has nearly four times the number of pixels as a camera that records in 1080p HD, which has a resolution of 1,920 by 1,080 pixels. For most UAS digital video cameras, 4K is the standard and that is often referred to as ultrahigh definition (Silva 2018). These cameras capture video that provides detailed imagery but requires higher-capacity storage capabilities. Understanding storage-capacity requirements is important when planning and executing an inspection to ensure enough memory is available for the desired task.

SENSOR TRAINING FOR QUALITY RESULTS

With the proliferation of commercially available UAS and their associated sensors, and given the ease of platform and sensor control designed into the systems, users may have the perception that using such systems for bridge inspections requires minimal preparation and training. However, employing a UAS sensor goes well beyond simply manipulating the platform controls and pointing the sensor at a location. To adequately capture visual information required for bridge inspections, team members must understand both basic as well as some of the more advanced principles of photography. Individual camera settings must be well understood to maximize sensor effectiveness. For sensors like those listed in table 1, training can be generally categorized in two ways: moderate and significant. Basic sensor training is available using documentation and instructional materials provided by the system manufacturer; this is generally inadequate in preparing the sensor operator to employ the sensor in support of a bridge inspection.

Moderate training typically includes the following activities:

- Prerequisite study applicable to the sensor, which may include:
    - Principles of photography.
    - Principles of thermography.
- Practical system operations training (2 to 4 h).
- Sensor and associated hardware flight training.
    - 20 to 30 flights.
    - 4 to 10 h of field training.

Significant training will include the following activities:

    - Prerequisite study applicable to the sensor, which includes principles of photography.
    - Principles of thermography.
    - Principles of LiDAR.
    - Other foundational science.
- Classroom and field training (1 to 2 weeks).
- Sensor and associated hardware flight training.
    - 20 to 30 flights.

In addition to these general training descriptions, the practices discussed in the following sections have proven useful in training personnel in the proper operation and effective employment of UAS sensors for inspection purposes.

EO/RGB Camera

A moderate level of training is sufficient to effectively employ this type of sensor. A basic knowledge of the principles of photography and the basics of aerial photography is very helpful in gaining operator confidence and will improve image and video quality.

Many features of camera systems are best learned through actual field training. General photography training for bridge inspection work can generally be accomplished in as little as 20 to 30 flights, or 4 to 10 h of field training. As with operating any piece of hardware, reading the manufacturer's user manual is highly recommended.

IR Sensor

A moderate level of training is also sufficient to employ an IR sensor. A basic knowledge of the principles of infrared thermography, as well as the basics of aerial photography, can be helpful in gaining operator confidence and ensure the quality of the images captured.

Like an EO camera, many of the features of an IR camera are best mastered through field training. In general, preparing the operator of an IR sensor for bridge inspection work can be achieved in 20 to 30 flights, or 4 to 10 h of field training. A basic understanding of the operational features is typically available from reviewing the user manual, which may take from 2 to 4 h.

To properly capture and interpret thermal imagery, thermography training is very beneficial. Various organizations offer thermography training, and it is organized according to different certification types for specific industry areas such as general thermography, security, and mechanical inspection. Additionally, some private-sector companies offer specialized UAS IR thermography training and certifications.

LiDAR Sensors

LiDAR sensors require a significant level of training to employ effectively. A basic understanding of UAS operations, mapping and surveying, and remote sensing is necessary to correctly collect UAS LiDAR data. Given the complexity of the system and the marked differences from EO or IR sensors, completing a course in LiDAR operations—typically including 1 to 2 weeks of classroom sessions and field training—as well as 20 to 30 successful training flights using the LiDAR and associated hardware, is necessary prior to employing the sensor for bridge inspection work. The system integrator or the provider of equipment can offer such training through in-person, web-based, and field training. This level of training can be expensive and requires a significant time commitment; however, well-trained, experienced technical staff tend to better understand operating principles and provide superior results with LiDAR.

Training courses for aerial photography, aerial thermography, and LiDAR operations are available through commercial vendors and educational institutions. Such courses are available via in-person and remote instruction.

CHAPTER 4. UAS PLATFORMS

UAS PLATFORM TYPES

Calling a UAS a "platform" is another way of saying it is an "aircraft," "design," or "model." As with sensors, numerous manufacturers produce a range of unmanned platforms. Several of the available platforms can serve as effective tools for bridge inspections; namely, multirotor, helicopter, fixed-wing, and hybrid vertical takeoff and landing (VTOL) platforms.

The most commonly recognized UAS type used for bridge inspections at present is the multirotor UAS, which will likely be the only type used for bridge component inspection. Multirotors are generally best suited for bridge inspections due to their great stability and the reliability of their electric motors. These platforms typically have between four and eight rotors that provide lift and directional control. One downside to multirotor systems is they typically have limited endurance (i.e., the length of time that a platform can safely remain airborne) when compared with other types of platforms. The power source, or battery pack, is generally the limiting factor. The weight of the platform, the wind conditions, and the outside air temperature all impact the performance of the battery and thus the endurance of the platform.

Single-rotor, helicopter-type UAS tend to have better endurance than the multirotor systems but may not be well suited for bridge inspections that require the UAS to fly close to the bridge structure due the large rotor diameter required to provide the necessary levels of lift and power efficiency. Additionally, single-rotor platforms can have limited options for the sensor positioning. Increased payload and endurance capabilities come at the cost of more vibration, which may make real-time data review more difficult.

Fixed-wing UAS have a long endurance capability but are unable to hover in one location. This limitation makes them impractical for inspections where static positioning is needed to acquire imagery, and thus they are the most limited type of platform for routine bridge inspections. These types of UAS are especially well suited for mapping and other tasks that require persistent or longer-range coverage. Thus, if an inspection of a river bridge requires a survey of the river characteristics both up and down stream of the bridge, a fixed-wing UAS may provide a viable solution. The inspection of long bridges may also benefit from the use of fixed-wing UAS, especially when a specific task, such as a deck-condition survey, is to be performed.

Some hybrid VTOL systems that can launch, hover, and land vertically and that can transition to fixed-wing flight to provide greater endurance are also available. At present, these types of systems are not well suited for bridge inspections in part because the wings make them very susceptible to wind effects when hovering. Also, endurance gains are only realized when most of the flight is in fixed-wing mode.

UAS CATEGORIES

The same three categories used in the chapter on sensors can be used to describe available UAS platforms: consumer, professional, and commercial. As described in chapter 3, these categories are not industry-standard terms; rather, they are offered to provide clarity for the reader and assist in determining the level of effort required to train personnel to a level of basic proficiency.

Consumer-grade platforms require little to no training to employ and cost very little in comparison to larger, more complex platforms. Flight training for these systems can be through manufacturer-provided training material or through a peer-to-peer training system that leverages the experience of proficient pilots.

Professional-grade platforms typically require some level of flight training and experience to gain the maximum level efficiency. An inhouse, standardized training syllabus can provide the necessary level of competence needed to employ these systems efficiently in bridge inspection scenarios. These platforms provide greater levels of stability during flight, allowing the user to produce a better-quality product.

Commercial-grade platforms are generally the most complex and capable, and operators may require a greater level of training and experience to effectively employ the platform than can be gained from day-to-day flight operations alone. Training for commercial platforms may be provided by the manufacturer, third-party companies, or through a standardized inhouse training syllabus.

Table 5 provides an overview of some key platform characteristics for each category that should be considered during the selection process, such as price, weight, and airborne endurance.

Table 5. UAS platform comparison chart.

Specification	Consumer		Professional		Commercial	
Cost	$799–1,099	$1199–1,499	$4,100–20K*	$999–1,499	$3,099–4,699	$4,999
Type	Multirotor	Multirotor	Multirotor	Multirotor	Multirotor	Multirotor
Weight	1.6 lb	3.0 lb	7.5 lb	4.3 lb	4.2 lb	19.8 - 20.9 lb
Max Weight	N/A	N/A	9.3 lb	4.3 lb	4.2 lb	34.1 lb
Endurance	27–30 min	30 min	23–27 min	25 min	28 min	16–18 min
Payload	Integral EO	Integral EO	EO	EO	EO, IR	EO, IR, LiDAR

* Prices will vary depending on the UA configuration and accessories.

PLATFORM SELECTION

When selecting a UAS platform, the criteria are practically identical to those used for selecting sensors (chapter 3). Selection criteria for UAS platforms are presented here as a minimum for consideration:

- *Budget*. Determining acceptable budget levels will provide a baseline criterion for the type and category of UAS to be acquired. Budgetary decisions should consider the platform's lifecycle costs along with its purchase price.

- *Experience*. Does the platform being considered require an advanced level of pilot experience to perform the task? The level of required experience can determine whether the UAS is within the skill range of the organization's pilots. Evaluating pilot experience may also aid in determining which category of UAS is needed.

- *Endurance.* The amount of time that at platform can stay airborne.

- *Gimbal Pitch Limit*. Several platforms available in the COTS market currently lack the gimbal ability to pitch the sensor up beyond 40 to 50 degrees relative to the horizon, limiting the ability of the sensor to provide the imagery required, especially when operating under a bridge deck. However, with proper planning and a skilled pilot, solid results have been achieved with systems that only pitch up to 30 degrees.

- *Payload Capability*. A bridge inspection may benefit from the ability to capture imagery using different sensors. Selecting a platform capable of carrying a variety of cameras or multiple sensors simultaneously may be practical for the organization.

- *Task Requirements*. Understanding exactly what tasks the platform will be performing will aid in determining what type of platform is needed. For example, knowing whether the platform will be used for a long-endurance mapping task or for tasks that require the ability to remain stationary will help determine the type of platform best suited for the inspection team.

- *Technology Obsolescence*. The UAS industry is very dynamic, with new and improved platforms being developed at a very rapid pace. The current rate of technology turnover runs on a cycle of 2 to 3 yr. This rate of change can have an impact on long-term UAS maintenance if the manufacturer stops providing software updates or producing the platform or parts to support it. To avoid the issue of obsolescence, it may be better to ensure that the platform acquired is not more than 1 or 2 yr old and is produced by a manufacturer with a reputation for supporting their products for several years after production stops. Acquiring a platform that operates using an open-source software architecture versus a proprietary software architecture may also increase the effective life of the selected platform.

- *Training*. The type, level, and duration of the flight training needed to effectively operate the platform may be an important consideration. Several types of training programs to instruct pilots on how to operate a platform are available. These range from OJT to formal instruction by a third party. Each method has its benefits and drawbacks that need to be evaluated, and the training selected should be commensurate with the level of complexity of the tasks to be performed. For example, OJT may be adequate for tasks like flying in a straight line or along a pre-programmed route, but will likely fall short of desired operational standards if the pilot will be required to fly in confined spaces, like those under a bridge deck, without the aid of Global Positioning System (GPS) information and a platform stabilization system.

CHAPTER 5. UAS OPERATIONS AND PLANNING CONSIDERATIONS

Planning for deploying a UAS in support of a bridge inspection is critical to maximizing efficiency, reducing cost and time, and ensuring the safety of the operation. The planning process (e.g., steps used, inputs needed, governing policies) will be up to the organization employing the UAS. The information contained in this chapter comes from multiple organizations, both government and industry, and has been included to help agencies implementing UAS as part of their bridge inspection programs achieve optimum inspection results. The workflows shown are not intended for a complete NBIS bridge inspection, but only for gathering information using a UAS. The best workflow would be a combination of parts from each of those listed.

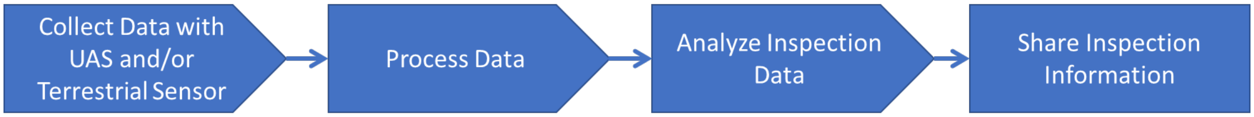
ESTABLISHING A WORKFLOW

Creating a UAS workflow will aid in establishing a plan to maximize efficiency during all phases of the inspection. The workflow itself will typically not change from bridge to bridge; its purpose is to aid in developing the inspection plan by highlighting each phase of the inspection or data-collection process.

The workflows represented in this section were developed for specific purposes, such as meeting regulatory and safety requirements or producing a specific imagery product.

The following examples have been tested and used by bridge owners and consultants for collecting data. They can provide a basis for the creation of a workflow that satisfies the requirements of individual organizations.

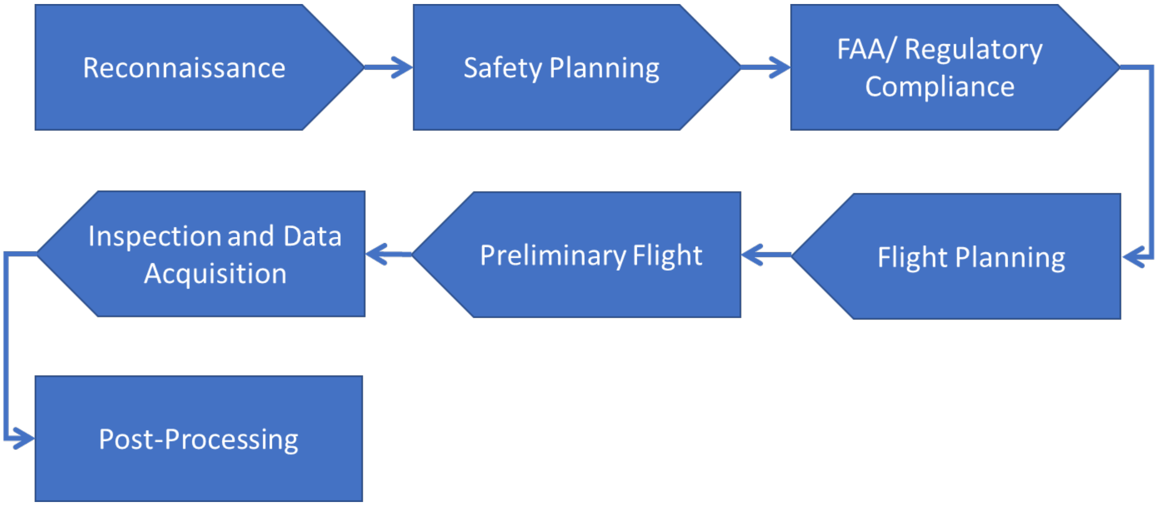
Figure 10 is a suggested general workflow used by the MnDOT and its engineering contractor. This workflow model is specific to the UAS flight, and the steps in the process that follow post flight.



Source: FHWA.

Figure 10. Diagram. General UAS workflow (Wells and Lovelace 2018).

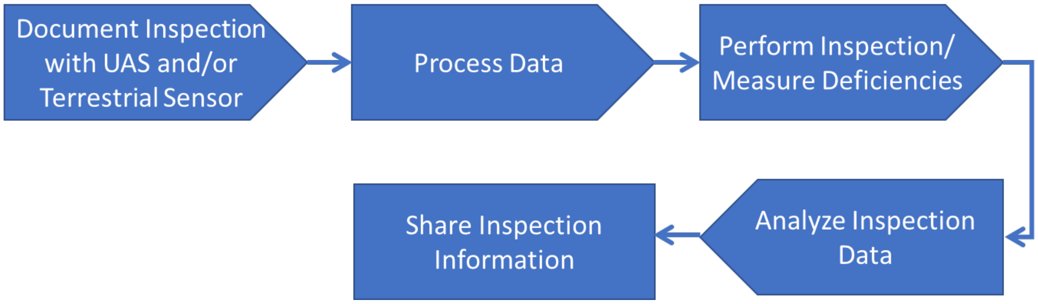
Figure 11 is a workflow used by ODOT and its research partners at Oregon State University to ensure that their inspection was in compliance with existing regulatory requirements and current safety practices. The workflow does not cover dissemination of inspection imagery, something that should be addressed if the products will be provided outside of the organization or department that is collecting them (Gillins et al. 2018).



Source: FHWA.

Figure 11. Diagram. ODOT UAS inspection workflow (Gillins et al. 2018).

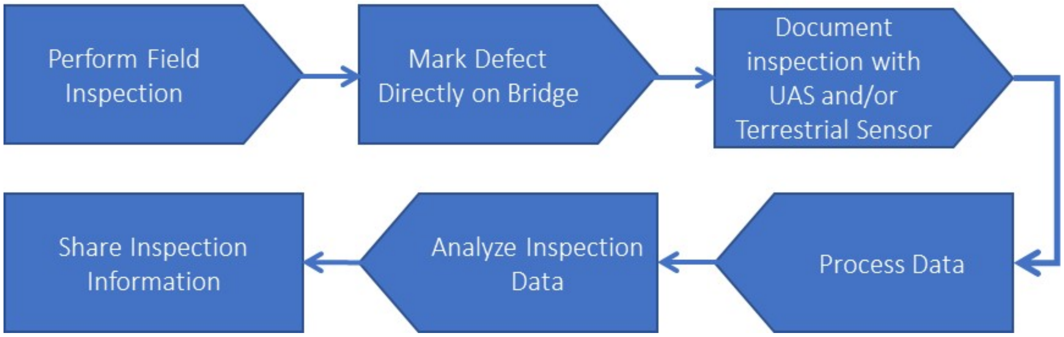
Figure 12 portrays a fly-then-inspect workflow used to fly the UAS and capture the imagery needed to create 3D models and other products that document the results of an inspection. The data are then used to create a dimensionally correct image, which is used by the bridge owner to view inspection results. The 3D model is especially useful for comparing bridge condition over several inspection cycles (Wells and Lovelace 2018).



Source: FHWA.

Figure 12. Diagram. Fly-then-inspect workflow (Wells and Lovelace 2018).

Figure 13 is a inspect-then-fly workflow used with traditional inspection processes that are supplemented with imagery captured by the UAS to document the inspection. This workflow can be used for creating photogrammetric models of bridges with imagery from UAS and terrestrial cameras. MnDOT has used this workflow to document the findings of an inspection where the defects were marked directly on the bridge. This method allows the user to create 3D and orthographic models and then capture measurements of deficiencies while in the office. These models are then available for comparison during future inspections (Wells and Lovelace 2018).



Source: FHWA.

Figure 13. Diagram. Inspect-then-fly workflow (Wells and Lovelace 2018).

Figure 14 is a hybrid workflow that also serves as a decision tree. The purpose of this workflow is to ensure that, if a defect or deterioration is found while employing a UAS during a bridge inspection, the defect is examined in closer detail by using other means, such as a UBIT, ladder, etc. This workflow will correspond most closely with a quality NBIS inspection.

Source: FHWA.

Figure 14. Diagram. Defect detection workflow.

PLANNING

Based upon an applicable workflow, the bridge inspector can craft an appropriate flight plan to optimize the UAS results. The plan for data collection and bridge inspection can be as simple or complicated as the planner decides is necessary to meet inspection goals. The planning process described in this section accounts for the minimum required steps needed to complete the tasks typically required for a bridge inspection involving a UAS.

- Pre-inspection planning items:
    - Identify the bridge (bridge type, location).
    - Determine inspection goals.
    - Determine required support materials and equipment.
    - Establish timeline and budget constraints.
    - Perform a review of previous documents (previous images, engineering plans, and previous inspections).
    - Coordinate with land owners and gain access to locations.
    - Perform site condition review (in-person visit, Google® Earth™).
    - Review other stakeholders' interests.
    - Plan bridge structure mapping (define flight path to ensure clear image documentation).
    - Identify deliverables needed including specifications (products needed to meet bridge owner requirements): high-resolution images, 3D models, orthophotos, etc.
    - Develop a shot list to determine what images need to be captured and in what sequence.
    - Establish the imagery product delivery method (local server, cloud, email, or digital media storage device).
- Flight operations/inspection plan and flight estimates:
    - Request airspace approval (if required).
    - Submit FAA Part 107 waiver (if required).
    - Estimate the time required per bridge element/component (with and without defect detection).
    - Determine UAS observer requirements beyond the typical team makeup.
    - Plan initial imagery analysis timeline, in the field (during the flight, in between flights, postinspection).
- Post data-collection steps:
    - Determine data transfer methods.
    - Determine image extraction process.
    - Determine image postprocessing requirements.
    - Estimate postprocessing in-depth analysis requirements.
    - Develop and complete bridge inspection report.
    - Determine method for dissemination of data to bridge owner.

FLIGHT OPTIMIZATION

UAS provide the inspector with the ability to capture great amounts of data regarding the condition of the bridge. However, launching the UAS, flying it to points of interest on the bridge, and then recovering it can lead to extra time and cost onsite if UAS use is not well planned and flights are not optimized to meet inspection requirements. To ensure optimal quality and quantity of data obtained using UAS, the inspection team leader should consider the following actions:

- Ensure the UAS pilots and sensor operators are appropriately trained to produce images that enhance inspection reports.

- Discuss any specific areas of concern with the team prior to the day of the inspection. If flown by a consultant, the bridge owner should ensure that the inspector and the pilot are on hand for the discussion, or at least are made aware of the specifics.

- Include the sensor operator and the bridge inspector in planning for UAS flights.

- Assign a notetaker to ensure proper cataloging of information associated with each image of a bridge component or element, including specifics on the defects shown.

- Review images after each flight or, at a minimum, prior to leaving the site to avoid having to return to capture additional images.

- Provide a sensor controller and screen for use by the inspector to enhance on site data collection.

- Incorporate techniques for managing the challenges presented with UAS flights over water. Flight over water can make maintaining a position for imagery capture difficult. Many COTS UAS have acoustic or optical obstacle-avoidance sensors meant to keep the UAS a certain distance (i.e., standoff distance) from obstructions. These sensors may be mounted on the top, bottom, or sides of the platform. UAS with bottom-mounted sensors may experience instability while operating in proximity to water. Because of this, disengaging the obstacle avoidance sensor may be necessary to capture the required images.

- Employ an additional observer when the situation requires; large and long bridge inspections are examples of such circumstances. If an observer is to be used, the crew should follow all the requirements for an observer detailed in 14 CFR Part 107 (CFR 14 107 2016). Communication between the pilot and observer is critical if the pilot cannot see the UAS.

- Select the platform and sensors based on the capabilities required for the task at hand. If available, a cage system around the UAS will provide some protection from collision with the structure and allow the pilot to move the platform up against the bridge to obtain very detailed images. Another capability that can add to the overall effectiveness of the UAS is modular or external lighting for use in areas with limited available ambient light, such as under bridge decks. (Lighting is discussed in greater detail in chapter 10.)

- Plan fully for operating the UAS during the loss of a GPS signal. Some UAS platforms that are very stable in flight when the GPS signal is lost; however, that is not the case for every platform. When operating around and under a bridge, a platform can experience a loss of GPS data. This GPS loss can cause the system to revert to a manual flying mode that is not stabilized, making it difficult to maintain a consistent distance from bridge elements. Unstable flight reduces the quality of the image and increases the risk of inadvertent impact with the bridge structure. It is also advisable to use propeller guards or a collision tolerant UAS in these situations.

OPERATIONAL CONSIDERATIONS

To achieve maximum efficiencies in time, money, and safety, it is important for the bridge owner and the inspector to address the conditions and parameters that impact UAS flight operations and thus can impact inspection results. This list is not all inclusive, but it provides a starting point regarding the UAS operational considerations that may impact an inspection:

- *Weather*. Weather can have several impacts on UAS operations. Cold temperatures can significantly impact battery life, reducing the platform endurance by as much as half. High heat impacts lift characteristics, making the platform motors work harder to maintain altitude, particularly in a hover. Rain and high winds may cause the platform to become unstable, limiting the usefulness of UAS. Thus, operating in mild conditions is recommended for optimum results. Flexibility in the inspection schedule is always a plus when weather is concerned. For specific limitations, users should refer to the operating instructions provided by the manufacturer. If operating limits are not provided, then the organization should define such limitations through a risk-based approach.

- *Structural Complexity*. The complexity of the bridge structure to be inspected can impact UAS operations in several ways, so the flight path needs to be well thought out during the planning process to ensure the inspection team views the entire structure. If the structures are large, tall, or have a complex architecture, it may take several flights to collect the required data, and the process may require an additional UAS observer to augment the inspection team. If the structure has utility service lines (e.g., water, electric, gas), it may require the inspector to gain physical access to the areas where the UAS is prevented from collecting imagery due to the presence of utility lines. These types of obstruction demonstrate the importance of ensuring that each bridge is a good candidate for inspection with a UAS and determining which areas can be inspected with a UAS and which areas require an inspector to view the physical location in person.

- *Regulations*. 14 CFR 107 includes guidance addressing UAS registration, operating rules, certification of pilots, and the flight waiver process (14 CFR 107 2016). The use of UAS for commercial purposes is evolving rapidly, and the regulations are under constant review and revision. It will be important for the UAS pilot and the inspector (if different from the pilot) to be familiar with these rules and to remain in compliance; "National Bridge Inspection Standards," 23 CFR Part 650 Subpart C, includes the standards required for performing a bridge inspection and references the AASHTO *Manual for Bridge Evaluation*, which outlines how to perform a quality bridge inspection (23 CFR 650 2004; AASHTO 2018).

- *Endurance*. Platform endurance (is affected by several factors, the most critical being payload weight. For many UAS models, a rule of thumb for time airborne is between 15 and 30 min. The heavier the sensor, or if multiple sensors are carried, the more platform endurance is negatively impacted. If a COTS system is modified to accept a heavier payload, then the user should expect the overall endurance to be reduced below the published specifications. Other factors impacting endurance are environmental conditions, particularly the mean elevation of the structure, and density altitude. The density altitude is the effective operating altitude taking into account outside air temperature; higher temperatures result in higher-density altitudes and lower performance. The higher the bridge mean elevation and density altitude, the harder the UAS must work to create the necessary lift to carry the planned payload.

- *Single-Sensor Configuration*. A UAS carrying a single sensor generally has a longer endurance than one carrying multiple sensors. However, the physical location of the sensor on the platform is important to maximize the potential of the UAS to capture the needed images. Sensors fixed to the platform below the rotors may not be able to "look up" sufficiently to image all locations underneath a bridge. To gain the maximum advantage from the UAS sensor, it should be able to be manipulated as near as possible toward 90 degrees above the horizon, or the level position, for the inspector to view the underside of the bridge superstructure.

- *Dual-Sensor Configuration*. Using a UAS with an additional sensor mounted on top will allow the inspection team to see surfaces that are out of a bottom-mounted sensor's field of view. The drawbacks of using an additional sensor include loss of endurance due to the weight increase, the added cost to upgrade the platform, and the increased risk of losing multiple sensors should a mishap occur.

- *Pilot-Observer Coordination*. If an observer is employed during a flight, the person is required to be in a position where they can maintain constant visual contact with the platform and constant positive communication with the pilot. Additional radios may be required to ensure proper crew coordination and communication.

- *Dual-Control Mode*. The dual-control mode is a UAS controller configuration where the UAS pilot and a sensor operator perform their tasks using separate controllers. This mode of operation generally maximizes the safety of the flight and the quality of the inspection results. The UAS pilot controls the UAS position during flight, ensuring the safety of the platform and the surroundings, and getting the UAS in position to attain the desired images and video. The sensor operator (typically the bridge inspector) controls the sensor actions to attain the desired images and video. This mode is recommended for most cases.

- *Single-Control Mode*. This mode is a controller configuration where the UAS pilot controls both the UAS and the sensor from one controller or control station. This mode might be used if the bridge inspector is also a certificated UAS pilot. In this mode, the pilot is responsible for not only navigating and controlling the UAS but also providing sensor control at the same time. Single-control mode is an acceptable mode of operation for some inspection needs but may impact the pilot/inspector's overall ability to document findings from the inspection, maximize UAS performance, and maintain safety of flight, especially when attempting to fly close to bridge elements. The UAS pilot should be a trained bridge inspection team leader in this situation.

- *Training*. Flying a UAS close to a bridge structure requires a high level of skill and proficiency in most cases. If the bridge owner is to operate its own platform using inhouse pilots, establishing a training and standardization program is recommended. Training programs carry costs associated with the time, materials, and equipment necessary to train each pilot. Additionally, while a certified bridge inspection team leader must be on site when a UAS is used for a bridge inspection, providing training to UAS pilots who are not inspectors on bridge inspection principles and techniques may also improve overall inspection-team performance.

- *Undesirable Lighting Conditions.* Low-light conditions under bridges also present a challenge to collecting imagery, particularly when using a daylight sensor. Many cameras have automatic settings that can manage varied lighting conditions where natural light is available and can adjust for shadows and low light to produce usable images. In confined spaces with no natural light or in very confined locations where natural light is too low, auxiliary light may be required to collect acceptable imaging. UAS can have auxiliary lighting systems incorporated into the platform. Some of these lighting systems are operated via a separate command link through a mobile device, while others must be turned on prior to takeoff. The benefits of such auxiliary lighting systems may come at the cost of endurance, however, due to the added weight and power requirements. Proper planning is required to ensure the UAS captures all desired data while minimizing the need to replace and recharge system batteries.

- *Equipment Maintenance*. Each system and camera will need to be maintained in accordance with manufacturer guidelines. Failure to do so could result in equipment malfunction or system failure at the most inopportune times. Of particular importance are the procedures used to charge and maintain the batteries, the most common power source for multirotor systems. UAS batteries are sensitive to temperature and to poor charging and discharging practices. Additionally, improper handling can lead to a battery fire or explosion. For these reasons, keeping maintenance logs to track the maintenance interval for each system is strongly encouraged. Having spare batteries and UAS parts onsite during an inspection will facilitate completion of all inspection tasks.

CHALLENGES TO USING UAS AROUND BRIDGES

Bridges present challenges to the inspecting organization using a UAS to effectively provide the information needed by the bridge owner. Some of the challenges are simple and can be managed on site, while others may require more complex solutions.

Bridge Obstructions

One of the simplest challenges to manage is ensuring that obstructions will not prevent the UAS from capturing needed inspection imagery or cause damage to the UAS. A preflight inspection of the bridge and the area around the bridge may be all that is required. An inspection team member may discover wires, fishing lines, or tree limbs that are not visible from a distance or via other resources (e.g., Google Earth). Preflight inspections aimed at discovering obstructions unknown during the planning process can save the inspector from unexpected delays, unsatisfactory inspection results, or the loss of the platform and sensor.

Under-Bridge-Deck Imagery

A significant challenge to the inspector is being able to collect imagery of the underside of the bridge superstructure. This inability is primarily the result of the sensor mount or gimbals on most UAS being placed on the bottom of the airframe. Such placement limits the travel of the gimbal and the ability of the sensor to collect desired images. While the travel limit, or the physical movement range of the sensor, is airframe dependent, most sensors using this configuration can only look approximately 40 degrees above the horizon, thus reducing the ability of the sensor to efficiently and accurately collect required data. To compensate for such limitations, some users have modified existing COTS platform to accept a top-mounted gimbal, and some UAS manufacturers are now producing systems with top-mounted sensors as well.

Collision Prevention

Unintended collisions with the bridge structure can damage the platform or sensor. Sense-and-avoid technologies are available to overcome this challenge. Additional sensors that either warn of proximity to an object or automatically reroute or stop the platform prior to a collision are incorporated into more complex UAS. As previously mentioned, some manufacturers have encased the UAS within a rigid grid structure, or incorporated rotor guards to prevent damage to sensors and rotors when flying in confined spaces. These technologies are available, but should not be used as a replacement for a qualified and competent pilot; instead, they should supplement the capabilities of the pilot and the UAS to ensure the requirements of the inspection task can be met.

Precision Georeferenced Data

Many UAS rely upon GPS information to maintain position for imagery capture and for capturing location information as part of the image. Use of GPS requires an unobstructed line of sight (LOS) between the satellites broadcasting the position information and the UAS receiver that is collecting the position information. When flying under a bridge, the LOS with GPS satellites may be interrupted, creating a loss in the fidelity of the position information and thus impeding the ability of the sensor to correctly add georeference information to the imagery. Thus, if a defect is detected under such conditions, the UAS position data captured along with the image may not be reliable should the inspector decide to revisit the defect with the platform. If GPS data is inaccurate and the inspector wishes to change or delete the position information, this may be accomplished by accessing the metadata and changing it there, although this will require additional software and time during postprocessing.

ADVANTAGES AND DISADVANTAGES

UAS have many uses across a wide array of industries. The techniques and processes used in these industries often mirror those used for bridge and other infrastructure inspections. Like any new tool introduced to an industry, UAS applications for inspections have advantages and disadvantages. These factors should be considered when determining whether the benefits outweigh the costs. The following list summarizes many of the advantages and disadvantages discussed in the report and discovered through this research and during interviews with bridge owners, inspection service providers, and sensor manufacturers.

Advantages may include the following:

- Reduces or replaces the need for traditional bridge access methods.
- Provides high-quality images to illustrate bridge defects.
- Reduces overall inspection costs for some inspections.
- Reduces inspection time requirements in the field for some inspections.
- Captures large amounts of data in a short period.
- Reduces or eliminates traffic control requirements, reducing hazard exposure to traffic control crews.
- Can easily access and inspect tall piers and view the entire bridge.
- Provides georeferenced images of defects.
- Improves safety for bridge inspection crews by removing or reducing human interaction with hazardous environments (fewer slips, trips, and falls).
- Capable of operating in tight and confined spaces (certain UAS configurations) or accessing areas not attainable by traditional means.

Disadvantages may include the following:

- Unable to meet inspection requirements for areas requiring physical inspection, such as sounding concrete or fracture critical hands-on inspections or because UAS access is restricted by the bridge element location.
- Needs additional planning prior to the inspection.
- Unable to detect certain minor defects, such as early signs of fatigue cracks in steel elements.
- Increases postprocessing time requirements due to large amounts of data.
- Requires extensive digital storage and archiving.
- Requires additional inspection team personnel if a UAS observer is needed.
- Operates with difficulty under the bridge due to loss of GPS signals.
- Requires certificated personnel to operate UAS for commercial purposes.
- Requires establishing a maintenance and training program to ensure system fidelity and pilot competence.
- Requires good weather (impacts to flight operations are significant during adverse weather).
- Yields low-quality images at a high cost (only applies to certain UAS models).

CHAPTER 6. DATA NEEDS OF THE BRIDGE OWNER

As previously presented, the purpose of integrating UAS into the bridge inspection process is to provide an alternative and, in many cases, an enhanced means of capturing data required for a complete, accurate, and compliant inspection. A UAS provides the bridge owner and the inspector the means of remotely positioning a sensor to capture data on a bridge structure. This chapter addresses the data a UAS can provide to meet the bridge inspection requirements of the bridge owner.

UAS data captured during an inspection can be used to update the structure's inspection records, identify and assess any new deficiencies, and update bridge repair recommendations. In some cases, UAS imagery of the entire structure has been used to assist in creating bridge "drawings" for older bridges where the original structural drawings no longer exist.

VISUAL AND NONVISUAL INFORMATION

There are two basic types of sensor information available to the bridge owner from a UAS: visual and nonvisual. Visual information means data used to produce a product that can be viewed by the user. Nonvisual data is typically measurement data collected to assess the soundness of the structure, but not to create visual products for inspection reports. Currently, visual information is by far the most prevalent form of information collected to support bridge owner needs.

Visual Information

At the current state of UAS and sensor technology, the primary type of data available to the bridge owner via an inspection is visual information via photo and video. Visual information is collected by various sensor types that detect electromagnetic energy—in some cases energy outside of the frequencies that can be seen by the human eye—including EO, IR, LiDAR, x-ray, radar, and synthetic aperture radar (SAR). Some sensors in these categories are available as COTS products, while others are specialized sensors manufactured for specific purposes. In general, UAS are limited to carrying sensors weighing less than 20 lb due to the FAA mandated 55-lb maximum takeoff weight for this category of UAS under 14 CFR 107 (14 CFR 107 2016). These sensors collect raw data used to generate various products to support bridge owners' requirements.

Inspectors can collect visual information and the associated geographic position information related to the images. Through postprocessing the images and videos captured by a UAS, the raw data can be transformed into actionable information or products that allow the bridge owner and engineers to see defects and meet inspection objectives. UAS images are inserted into the inspection report like imagery captured on a handheld digital camera. Other products like photogrammetric point clouds and associated meshes can be provided to the bridge owner in addition to the inspection report, either in an online viewer or as separate files that can be opened and analyzed using various desktop programs, such as a photo viewer or image processing software.

Features of sensors used to collect visual information can enhance the inspection process. Digital camera sensors can provide very detailed, high-resolution images of the bridge and its components using the visual light spectrum. These images can be digitally magnified during viewing on an HD system postflight, allowing the inspector to view very fine details of a surface without having to be physically within arm's reach of the structure.

Live-feed UAS video received via the downlink in definitions as high as a 1080p can provide a high-quality picture that allows the user to see significant detail in real time when using a capable monitor. A live feed also allows the user to blow up the image on a large format display.

Variable optical magnification can be achieved by employing a system with a lens having a variable focal length instead of a fixed focal length. These systems can be beneficial to inspectors as they can zoom in on areas of interest mid-flight without the need to maneuver the platform closer to the subject or land and swap to a longer focal length lens.

IR sensors detect energy invisible to the eye; however, the visual images created by the camera system can present unique visual information for the bridge owner regarding changes in bridge structures. Several bridge owners have employed IR sensors, both experimentally and in practice. A common use of an IR sensor at this stage of UAS deployment is to view areas of a bridge deck's concrete and other surfaces that exhibit difference in temperature, such as concrete girders showing signs of deterioration, or to back up findings identified using traditional inspection methods, such as the chain-drag process.

UAS data captured by LiDAR can be used to produce detailed, dense point-cloud renderings of structures. Geospatial software programs and CAD can then be used to create a 3D visual representation of the bridge in which accurate measurements can be made.

Nonvisual Information

The second type of sensor information usable to the bridge owner is nonvisual. Such sensors include ultrasound, radio-frequency sensors, magnetometers, and eddy current. UAS are either currently not capable of carrying these types of sensors or the technologies are in early stage development as UAS payloads. One such system in development is a UAS that uses an electromagnet to hold the platform to a metal surface to help stabilize its position, while an ultrasound sensor payload tests the thickness of the component (Mattar and Kalai 2018). Advances in UAS technologies envisioned or in development are discussed further in chapter 8.

QUALITY AND QUANTITY OF DATA

A UAS can provide the bridge owner and inspector a tremendous amount of very high-quality imagery in support of bridge inspections. While high-quality imagery is a benefit, the amount of data provided to the inspector can present challenges.

When looking at the use of UAS to capture inspection data, it is important that the inspection team leader and the UAS pilot (if that person is different from the inspector) be fully engaged in both inspection planning and actual field operations. The team leader has complete responsibility for the bridge inspection and will have the specific information on inspection requirements. That person will determine whether the correct imagery and amount of data are collected as well as whether the image quality is high enough to meet requirements for the inspection report.

Data Quality

High-quality data enhance the inspection results and associated reports by allowing inspectors to identify small defects before they become larger problems. Image quality is affected by both the sensor specifications and the sensor operator's ability to properly adjust settings to account for ambient lighting conditions and platform motion.

Image quality can also be affected by improper subject framing. Therefore, it is critical that the UAS pilot and inspector work together to position the platform to capture the image from the perspective the inspector needs.

Environmental conditions—e.g., dark, light, hazy, clear, low sun, high sun, cloud cover—impact required sensor settings, such as ISO, shutter speed, and aperture setting. The ISO setting determines how sensitive the sensor is to light. Generally, the darker the scene the higher the ISO setting needs to be. The ISO can aid in bringing out defects in poorly lit areas under a bridge but will wash out the image in brighter areas. Higher ISO settings result in grainier images; at some point, increased ISO has a negative effect on image quality. Most cameras have automatic adjustments available; however, the automated sensor settings may need to be overridden in certain conditions through manual adjustment to obtain the image fidelity needed. Since the settings may need to be adjusted during flight, the sensor operator must have a working knowledge of the basics of photography to ensure optimum image capture. A source of external lighting mounted on the UAS may reduce the need for manual manipulation of the controls; however, depending on ambient lighting conditions, manual adjustment of the settings may still be required.

Differing opinions exist as to the most important sensor specifications for ensuring the quality of a UAS image meets inspection needs. A common requirement from experienced consultants is an EO sensor capable of taking no less than a 10 MP photo and capturing 4K video. Studies on the use of UAS for inspections in Minnesota found that the experience and judgment of the inspector is the most important factor in determining the condition of a bridge component or element from an image and not necessarily the sensor resolution itself (Wells and Lovelace 2018).

Other factors also impact the quality of the imagery obtained by a UAS. The ability of the pilot (or the UAS in an autopilot mode) to fly a consistent, fixed distance from the bridge at a speed that maintains focus on the member being inspected; the experience of the camera operator; and the ability of the sensor to capture quality images in poorly lit areas (such as under a bridge) are all factors impacting the quality of EO images.

Capturing high-quality IR images may require different UAS and sensor operation techniques. An IR sensor can be beneficial in identifying thermal discontinuities indicative of delamination in bridge decks and other structural defects. Employing improper IR techniques could induce false negatives or positives in the image, however, thus rendering the images useless. Transient thermal conditions, or conditions that create temperature differences within the structure as well as between the structure and the surrounding environment, are required, but such conditions are affected by time of day, weather, and surrounding environment (e.g., the presence of shade-causing objects that can affect temperature).

During proof-of-concept inspections performed in Utah, inspection teams employed UAS with IR sensors very close to dawn or dusk to enhance the heating differentials. According the to lead UAS coordinator and technology advancement specialist for Utah DOT, a uniform surface or bridge deck is key to obtaining high-quality IR imagery. Any nonpermanent barriers, cones, or barrels can cast shadows and disrupt the quality of the images. Even traffic crossing the bridge can create temperature differences (due to vehicle tires), which can be detected by an IR sensor. IR images should be captured using thermography techniques employed by a trained UAS sensor operator to maximize IR image quality and value to the inspection.[3]

Data Quantity

The amount of data a UAS sensor can collect can be enormous. During a single inspection of a long bridge, imagery and information totaling more than 50 gigabytes (GB) may be stored or transmitted by some sensors. Thus, it is important for the ultimate owner of the data to determine organizational data storage and transfer capabilities so that the amount of data collected does not degrade the advantages of using the UAS.

A "more is better" operational approach to UAS-collected data is not necessarily the best option. Reviewing the bridge's historical file during inspection planning, so the condition of the bridge is well understood, will aid in estimating the imagery products required. It may be beneficial to focus on known structural issues by capturing the images needed to track the status of the deficiency and determine its progression.

Collecting numerous images for every bridge component and element may require additional flights and extra time to sort through the data and ensure the correct images were captured. The burden of large amounts of data collected using UAS can be alleviated by ensuring the inspector has adequate means to view the imagery as the flight is occurring or immediately after each flight. Using dual controls during the flight or having an HD monitor in the field, perhaps located in a darkened vehicle cab, where the images can be viewed in between flights directly from the memory device used in the sensor, is one way to ensure the inspector has access to the imagery being captured.

Ultimately the quantity of images required will be determined by the products requested by and the desires of the bridge owner. If a 3D model, video, or detailed orthomosaic is desired, a greater amount of raw data will be necessary than if high-resolution photos alone are requested.

As artificial intelligence (AI) and machine learning technologies mature, managing large quantities of data should become less of an issue. AI may provide a more efficient means of organizing and extracting needed information within large data archives, reducing the burden on personnel associated with completing these tasks manually.

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[3] Interview with Paul Wheeler, lead UAS coordinator and technology advancement specialist, on October 2, 2019.

COSTS AND RECORD KEEPING

Two potential benefits of employing UAS for inspections are cost savings over traditional inspection methods and the accuracy of location information when defects are discovered.

Impacts on Inspection Costs

The impact of UAS on the costs associated with bridge and infrastructure inspections has been documented by multiple studies, with both positive and negative impacts found (Gillins et al. 2018; Dorsey 2016; Wells and Lovelace 2018). Various studies identified cost benefits in both monetary savings and personnel time requirements. The parameters within which these cost-saving values were determined may be different than what some owners would suggest to fully complete a bridge inspection, however. The values were taken from the studies as indicated and should not be construed as typical. Actual cost savings must be determined for each unique situation. Some of the specific findings these research efforts documented include the following:

- An analysis conducted by Oregon State University for the ODOT identified a cost savings of around $10,000 per bridge and a time savings of 10 percent. (Gillins et al. 2018) In one example, a bridge inspection performed using UAS saved $3,900 in hourly labor costs, $2,800 in equipment rental fees, and $3,500 in traffic control costs, resulting in a total savings of $10,200.
- A 2016 report by AASHTO found that using UAS resulted in cost savings of $4,350, a personnel reduction of two people, and a time reduction of 6 h for a standard bridge deck inspection (Dorsey 2016).
- MnDOT conducted a cost comparison of an inspection employing traditional access methods, including UBITs, personnel lifts, and other access means, that cost approximately $59,000 and would require 8 d to perform. This cost was compared with that of a UAS contractor conducting the inspection for $20,000 and spending only 5 d on site, resulting a 66-percent cost savings and a reduction of 3 d in personnel time (Wells and Lovelace 2018). In the final phase of MnDOT's study, researchers determined that the use of UAS resulted in an average cost savings of 40 percent and an increase of 2 percent for personnel time (Wells and Lovelace 2018). The increase in personnel time was a result of additional imagery processing and analysis time requirements.

There are cases, however, where using UAS did not save time or money. For example, a bridge inspection in Idaho involving a hands-on fracture-critical member cost $1,564 for a UBIT and took 4 h to complete. This cost was compared with a UAS-assisted inspection, which was only able to complete approximately one-quarter of the inspection in 4.5 h at a cost of $200 per hour, or approximately $1,800 to complete the entire bridge (Dorafshan and Maguire 2018).

Other costs associated with the employment of UAS are not discussed at length in the available documentation or research, but will impact the bridge owner. Some of these costs include the following:

- Initial UAS cadre training.
- UAS pilot proficiency and currency flights to ensure skills do not degrade.
- Consumable UAS parts like propellers and batteries.
- Multibattery charging systems.
- Specialized payloads.
- Replacement cost of airframes damaged in mishaps.
- Electronic tablets or computers for ground station support.
- Mission planning software.
- Survey support equipment like ground reference point markers or survey GPS.

These costs are specific to UAS operations and will vary in amount and frequency of outlay depending upon the type and number of flight operations the organization conducts. If a contract UAS operator is used by the bridge owner, such costs would be included in their overhead charges.

Defect Location Data Records

Precise location information on bridge defects is required to ensure accurate identification in inspection reports and to locate these defects during subsequent inspections. When using UAS during an inspection, this can be accomplished by either labeling each image using the nomenclature in the original bridge design documents or ensuring the image labeling is consistent with previous inspection reports.

Bridge owners typically have policies or requirements on how to document photos from their bridge inspections. These policies specify the nomenclature that should be used for bridge units inspected, such as identifying the numbering orientation of girders. The same requirements should be followed for UAS-captured images. One technique to accomplish this is to make a field/photo log of the images and label each with a number, the specific bridge element, and the distance relative to another significant bridge feature. Such a log would enable the inspector to identify where each image is on the structure rapidly. As an example, a field log entry for the position of a defect might read as follows:

> *2nd girder from west fascia, 12 ft south of the north abutment bearing on the east face of the girder*

This practice also helps ensure the repeatability of the information gathering process.

The position coordinates of the UAS at the time the image was captured can be recorded postflight from the metadata, which will also aid in the repeatability of the inspection imagery; however, this requires a solid GPS signal. If the GPS signal is weak or lost, the data may be inaccurate or absent. Additionally, camera settings should also be noted in these types of situations to ensure the quality of the imagery is also repeatable. These are some of the advantages of using UAS over traditional inspection photo logs.

CHAPTER 7. UAS DATA MANAGEMENT

When employing UAS during bridge inspections, the data captured by the sensors require storage, postprocessing, analysis, and dissemination—and the amount of data captured can be massive. State DOTs leading the way in the use of UAS for bridge inspections have discovered that managing the data they collect can be the most challenging aspect of using this inspection tool. This chapter discusses aspects of data management bridge owners and inspectors can use to optimize the use of UAS for inspections.

DATA MANAGEMENT PLAN

The first step in managing large amounts of information is the development of a data management plan. A data management plan outlines the types of data to be created, the data formats and metadata standards to be used, personnel responsibilities, data security and sharing procedures, duration of data retention, data storage methods, data transfer methods, and the costs associated with each element of the plan.

Data management plans are usually brief and address the management needs as they apply to an individual inspection. A listing and description of the plan elements is provided here.

- *Data Types*. The most common types of inspection data collected will be high-resolution photos and video. The postprocessed data will be in the form of 3D models, 2D orthoimages, high-resolution images and video, and LiDAR point clouds.

- *File Formats and Metadata*. The data file formats most commonly used include JPEG, TIFF, RAW (proprietary to each camera manufacturer), MP4, LAZ, DOCX, XLSX, and PDF. The file format used is sensor- and system-software dependent. Since the associated metadata are system generated, it will comply with industry standards for imagery and video and is captured by the internal system software. Additional metadata required for inspection analysis and reports but not captured internally by the system must be captured externally and input into the file comments or recorded as a file on a separate spreadsheet.

- *Access, Sharing, and Privacy*. Access to all data is generally coordinated through an organization's controlling custodian. Data-sharing practices must account for security needs; the privacy of property owners must be a priority, and personal data collected must be kept in accordance with applicable local, State, and Federal guidelines. Each organization approaches information sharing differently; for some, information is readily shared, but other owners require secure access. Published bridge safety inspection reports can and have been shared via websites, with an example being the site used by MnDOT (MnDOT 2020). This is not typical for most owners, however.

- *Retention*. All inspection data can be kept in a "bridge file" in accordance with bridge owner and departmental recordkeeping guidelines. The data retention requirements must be spelled out in the data management plan for the project.

- *Storage*. Inspection images collected by the UAS in the field are initially transferred to a laptop or tablet while in the field. Once the field inspection is complete, the raw data are typically transferred to a local server or removable storage device. Following postprocessing, select processed data products (such as cropped high-resolution images, 3D and 2D models, or orthoimages) may require saving to a separate, defined storage space, like a departmental server or the cloud, to be made available for additional analysis or for reporting purposes. All data and data products should be backed up on a secure medium, such as a secure cloud service.

- *Data Transfer*. Raw and processed data products are transferred via a controlled site. This transfer of raw and processed data may be through a third-party site where processed data products can be viewed and used, via email, or through a shared cloud service (North Carolina State University n.d.).

Developing a data management plan in the early stages or prior to introducing UAS into bridge inspection processes can ensure the inspectors capturing data have a standard approach for collecting and transferring the data, a known and secure location and structure for storing and retrieving the data, and a well-understood process for sharing the data and inspection products generated by the UAS.

FIELD DATA COLLECTION METHODS

A skilled, certificated UAS pilot enhances the likelihood of successful UAS flight operations for bridge inspection. A proficient, experienced pilot ensures the safety of the crew, compliance with current regulations, and a quality end product for the bridge owner while lowering the risk of losing equipment. The most successful inspection teams use a dual-control setup and include a qualified inspection team leader and an experienced UAS pilot. Examples of how UAS data can be captured in the field by inspection teams using different controller setups are presented in this section. These examples take into account the situation anticipated during the inspection as well as the flight plan developed prior to the inspection.

Dual Control

The dual-control inspection team comprises a UAS pilot and a sensor operator who perform their tasks using separate controllers. The sensor operator in this scenario is the bridge inspector. The UAS pilot controls the UAS position during flight, ensuring the safety of the platform and the surroundings and getting the UAS in position to attain the desired images and video. There are two video feeds from the UAS in this setup: a “first person view” (FPV) camera for the UAS pilot and a second high-resolution camera capable of viewing the live feed and capturing inspection video and photos for the bridge inspector. The bridge inspector directs the onboard camera and can, while the platform is in flight, adjust the gimbal angle, the zoom (if equipped with variable focal length lens), and multiple camera settings to achieve the highest quality inspection imagery possible.

Figure 15 depicts a bridge inspector working in coordination with a UAS pilot. Using dual controls, the inspector can focus on capturing the needed images of the bridge structure while the pilot concentrates on safely flying the platform.

Figure 15. Photo. Dual control UAS operation.

Single Control

For less complex bridge site situations, a single-control UAS may be perfectly capable of capturing inspection-worthy results. In these systems, all UAS functions are controlled by a single UAS pilot, ideally a qualified bridge inspection team leader. In this setup, the UAS pilot is flying the platform and operating the sensor. If the UAS pilot is not a qualified bridge inspection team leader, a preferred system setup would typically offer duplicate video feeds for the inspection team leader to observe the UAS video during flight. Otherwise, the team leader will need to constantly look over the shoulder of the pilot. With constant communication between the UAS pilot and Team Leader, quality video and photos can be captured. This method of data collection may require additional postprocessing time to generate the products for the final inspection report as compared with the dual-control setup.

Live Stream Data Collection

The ability to livestream UAS video to remote locations is a data-collection technique in development that offers advantages over the onsite dual- and single-control setups. Livestreaming allows the client, potentially the bridge owner not present at the bridge site, to see what the UAS inspection team sees in real time. This process offers advantages in some inspection situations, whether for inspection purposes or simply to convey the value and capabilities of the UAS to the client.

UAS available with the capability to livestream wirelessly to online platforms such as YouTube and to services that support Real-Time Messaging Protocol. Such systems provide the means to view encrypted video from remote locations and view the inspection imagery as it is captured. While the video streamed is at a lower quality (typically 720p versus 4K), remote viewers can view the bridge asset and communicate with the UAS pilot (or additional personnel on site) to request additional data on specific areas of interest, if necessary.

Another benefit of live streaming is having the ability to showcase the capabilities of the UAS to a wider audience. For many bridge owners, typically only a select few within the organization get to work with the UAS operators and see the technology in action. Being able to livestream the inspection is an effective way to include additional experts, who can tune in to the flight and see the inspection taking place, virtually. The livestream also captures audio from the phone or tablet being used as a monitor. An audio feed also allows the pilot or sensor operator to communicate the flight plan and inspection findings as a voiceover in real time.

Livestreaming is not always a viable option for a bridge inspection, however. It requires a reliable internet connection, and while Wi-Fi tends to be the fastest and most reliable connection, many bridge sites do not have wireless internet connectivity available. Wi-Fi frequencies also may interfere with typical 2.4 GHz and 5.8 GHz UAS command and control links. A 4G LTE signal generally offers sufficient data transfer rates, but will not provide the same quality or latency video when compared with a faster Wi-Fi connection. The quality of the video continues to degrade as internet speeds decrease, which can be frustrating for all parties involved.

Regardless of internet speed, at present video streaming is typically limited to 720p quality. In most cases this is satisfactory for the intended purposes, but it makes it more difficult for remote personnel to spot hairline cracks or other small structural deficiencies. The video being recorded locally to the SD card onboard the platform records the full resolution for later review.

Even with the lower resolution, however, there is still minor latency between real time and the video feed being viewed by the client. With faster internet speeds, there can be a delay of 1 to 2 s. With slower speeds and older hardware, that delay can increase to 30 s (or more) and users may experience dropped signals. The greater the signal latency, the longer the inspection may take and the greater the impact on the endurance of the platform. Delays of more than 10 s or frequent signal loss may make coordination between the remote team and field team difficult or impossible.

IMAGE TRACKING AND DOCUMENTATION

Field logging and documenting captured images is a key task in managing UAS data. When an inspector is evaluating a bridge using traditional methods and takes an image of a defect using a handheld camera, the inspector can manage the images in real time and easily record the position on the bridge structure being imaged on a plan or in the inspection notes. Often an inspector can write notes directly on the structure near a defect before a photo is taken. These notes act as a backup to the photo log so that the location is documented in the photo. When UAS are utilized for a bridge inspection, the inspectors may not have this ability, so the process of tracking the positions on the bridge being imaged becomes even more critical.

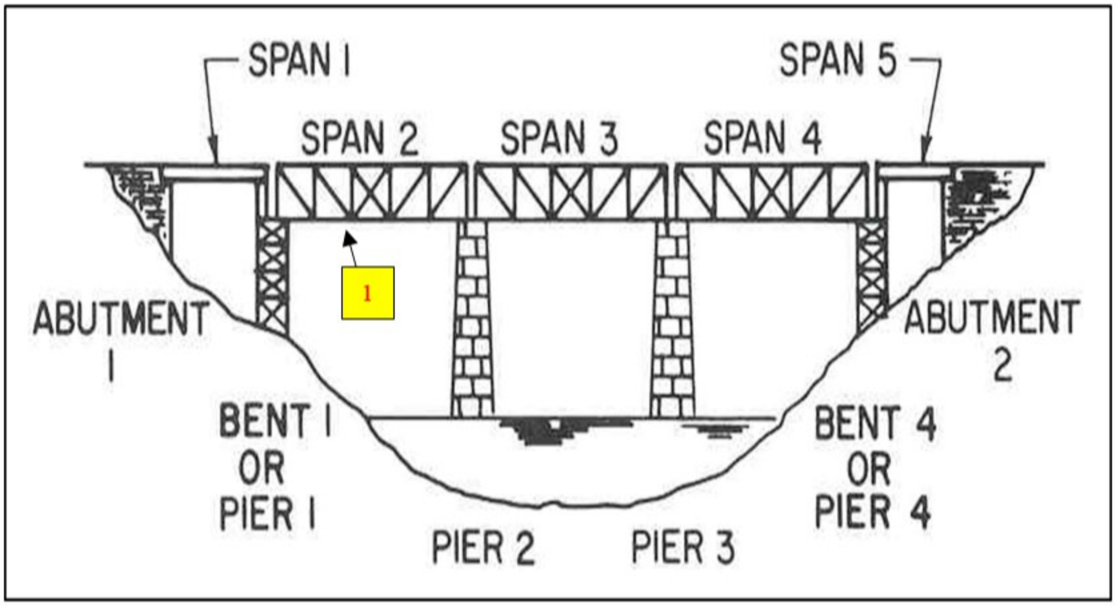
Various methods can be used to track the location of images captured during an inspection. Regardless of the process used, it must facilitate the correlation of the image to the specific location of the defect and be both standardized and repeatable. Repeatability will allow the inspector to reposition the UAS to collect additional images later to compare and evaluate the condition of the bridge element or defect over time.

One method for tracking images is to generate and document the flight plan by mapping the route on a sketch, an aerial image, or a bridge plan, and then making note of any deviation from the plan after each flight. An assistant inspector or notetaker can use the depiction to record the sequence of the bridge components or elements captured during flight and the direction from which each photo was taken. To separate image sequences after a complete end-to-end flight, the sensor operator can take a downward-facing image denoting the end of that set of images. Individual flights can be easily identified in a similar manner by taking a photo before launching.

The notetaker should have a sketch, diagram, plans, drawing, or image of the bridge that can be annotated with the image number, the physical location on the bridge, and the noted defect.

Figure 16 is an example of a diagram that could be used for notation and tracking image locations as the inspection is being conducted. This diagram is taken from the BIRM (Ryan et al. 2012). Copies of the actual bridge drawings, simplified sketches, and photos may be the best resources for recording structural defects as they will more accurately represent the bridge in its current condition. For this example, the notation for the location of a defect (denoted by the yellow box labeled "1") could be written as:

Image 1; Span 2; L1 outboard gusset plate connection to member U2, missing rivet.



Source: FHWA.

Figure 16. Diagram. Example bridge diagram correlating to field notes.

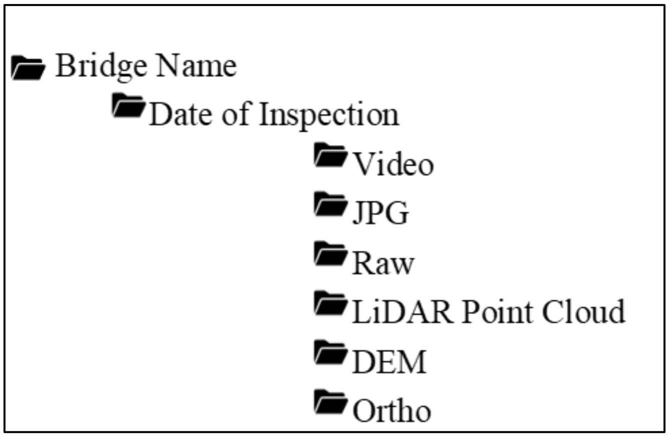
Again, the purpose of creating field notes on captured imagery or diagrams is to enable the inspector to effectively document, evaluate, and quantify the condition of the bridge elements. Availability of such notes increases efficiencies and saves time in the creation and delivery of the inspection report and in the follow-on processing of other imagery products. This documentation gives subsequent inspection teams a basis for documenting the presence and progression of defects.

CATALOGING

Cataloging is the process of creating a directory of stored imagery files to be recalled later. Cataloging also includes identifying where the data are located and the types of data stored, establishing a process for version control, and instituting file-naming conventions to which all users will adhere.

File Directory

For imagery products, a standard file directory, like the example shown in figure 17, may be sufficient for most projects. Such a directory is easily understood by most users as it mirrors the types of organizational practices most computer users employ in their daily work to organize data files.



- Bridge Name
  - Date of Inspection
    - Video
    - JPG
    - Raw
    - LiDAR Point Cloud
    - DEM
    - Ortho

Source: FHWA.

Figure 17. Illustration. Example image file directory.

Given the large size of the files users will store using this type of directory, it may benefit the organization to regularly monitor the directory and folder sizes. If UAS images are stored on an internal organizational server, the available storage space can be managed effectively by examining stored files for relevance prior to cataloging new images after an inspection.

3D Model as a Catalog

A more advanced method of cataloging images is in the use of a photogrammetric, 3D model of the bridge. This method is an alternative that allows all the inspection images for the entire bridge to be stored as a 3D model. The bridge section of interest where a defect exists can be selected on the model, and the image can then be brought up for analysis. MnDOT and its supporting inspection contractor have tested this method of cataloging images (Wells and Lovelace 2018).

To catalogue the images in this way requires creating a photogrammetric point cloud. Creating this point cloud entails capturing imagery for the entire bridge with sufficient overlap (75 percent or greater is recommended). Depending on the size of the structure, this may require thousands of images to be captured and processed, significantly increasing time on site and in the office. This method may not be well suited for certain types of bridge structures (e.g., very simple (homogenous surfaces) and very complex geometries) as current photogrammetry software tends to struggle to stitch together such models.

Figure 18 shows an example of MnDOT's use of imagery cataloging via a selectable 3D model (Wells and Lovelace 2018). To use it, the inspector clicks on a particular point in the model and views images that contain that point on the structure. The image can then be inspected for defects. This type of software can reduce the need for a manual photolog since the photogrammetry software will locate the image on the structure.

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Figure 18. Illustration. Example of a 3D bridge model with selectable image locations.

File Naming Conventions

At first glance, naming a file would appear to be an intuitive process. However, because there are so many variations in file naming conventions, it can be difficult to keep information organized, especially when multiple agencies or personnel are involved. When multiple personnel are involved in a project, the best solution is to standardize a naming convention and apply the convention to all the files that will be collected.

Some general rules of thumb for creating a useful, repeatable naming convention include the following:

- Be consistent.
- Do not change the convention once established.
- Create a document that details how the schema should be applied.
- Keep the length below 32 characters.
- Use underscores to create a space or “camelCase” in a file name.
- Avoid special characters as they can confuse analysis programs.
- Apply the same date format to all files (e.g., YYYYMMDD).
- Use zeros in version control numbers and sequential numbers.

Following these rules, an example file name might be as follows:

> *BridgeID_20181101_v01.jpg* (Malinowski 2018).

This method is a best practice used by Massachusetts Institute of Technology Libraries; however, it may not provide enough description to be able to catalog geospatial and image files. If that is the case, then the organization will need to develop its own convention.

The MIT convention is not the only naming convention that works. Another option is to use the location of the bridge component as the basis for the file name:

- Photogrammetry and LiDAR products: Date – Project location/Name – data type – coordinate system.
- Image products: Date – Project location/Name – location of photo on bridge.

Following these rules, an example file name might read as follows:

> *20200704_VA-James-City-County_Rt-5_Chickahominy-River_Pier-2_South-Face.jpg.*

Whichever method is chosen, the naming convention for inspection files should be applied in a consistent manner and incorporated into the organization’s operating rules.

Batch Renaming

To aid in cataloging so that images can be readily cross referenced with field notes after an inspection is complete, image files can be renamed in accordance with the designated naming convention by using a batch process. The batch process aligns the images with the component or element of the bridge to which they correspond and relabels the files as a sequence of images using a batch naming program or the built-in batch naming function available in Windows.

This method of batch renaming can be done on Windows 10 operating systems. The steps are as follows:

1. Create a folder with all the images to be renamed.
2. Select all the images, starting with the top or first image.
3. Right click the mouse on the top or first image to bring up the options menu.

4. Select “Rename.”
5. Enter the new name for the files.
6. Select “Enter” key.

This will give all the images the same name and add a sequential number in parenthesis at the end of the image name.

Using the previously cited contractor naming convention for image products, a batch renaming process with Windows might result in the following change:

- Original sensor generated file name:
    - 20180101_084923.
    - 20180101_084924.
    - 20180101_084925.
- Batch renamed images:
    - 20180101_Anytown Bridge_Span 3 (1).
    - 20180101_Anytown Bridge_Span 3 (2).
    - 20180101_Anytown Bridge_Span 3 (3).

Note that the images’ sequence is in parentheses. Complete and consistent field notes are required to ensure each renamed image matches the inspector’s notes.

Batch renaming applications may prove beneficial if the current naming convention is changed by the bridge owner. More sophisticated renaming schemes can be achieved using tools such as Bulk Rename Utility.

File Formats

Dozens of file formats are currently available. When choosing the format that will best serve the management of UAS inspection data, care should be taken to use formats that are reliable, maintain the original image fidelity, and will be useful during successive inspections. Being usable during future inspections is an important selection factor given the rate of technological advancement. The bridge owner and inspection personnel need to be able to compare images taken years apart to evaluate changes, and switching to a different file format may complicate this process. Table 6 shows several of the more common file formats available by product type.

Table 6. Imagery product type file formats.

Product Type	File Format
Video	.mpg, mp4, .mov, .mpeg4
Photo	.tif, .tiff, .jpg, .jpeg, .raw, .dng
DEM	.tif
LiDAR point cloud	.las, .laz
Orthoimages	.tif, .tiff, .jpg, .jpeg

Even though the file formats in table 6 are considered common, it is important to note that technology changes rapidly, and these file formats may not be supportable in the future. File formats likely to be accessible in the future will typically have the following characteristics:

- Nonproprietary.
- Open, documented standard.
- Commonly used by research communities.
- Standard representation (ASCII, Unicode).
- Unencrypted.
- Uncompressed.

The following file formats are examples that meet the above criteria:

- MPEG-4.
- TIFF or JPEG2000 (not GIF or JPG).
- CSV.
- XML.

INTEGRATION WITH EXISTING BRIDGE MANAGEMENT OR INFORMATION SYSTEMS

In general, an inspector will use a standard inspection report format that contains NBI data items and complies with the bridge owner's policies and standards. When using a UAS to augment an inspection, it is the imagery captured by the UAS sensor and selected by the inspector that will be included in the report. Thus, using a UAS for inspection purposes should not generate an additional paperwork burden, even assuming the information and defects found in the images will be documented in the inspection notes and element quantities. Once the inspection is completed, the images selected for the inspection report will be input into the information system when the report is created. For many DOTs, the system they use for collecting bridge inspection data generates a report consistent with the NBIS.

Depending on the owner requirements for storing the entire UAS file, it may be necessary to forward all images and video to the bridge owner on a portable memory device to be archived on a local network or approved cloud storage location for the bridge file once the project is complete.

In addition to providing imagery for inspection reports, UAS data can feed into a bridge management system (BMS). The data products that can be created using UAS images, such as 3D models, can be used to track deterioration over time with geospatially referenced images to remove any guesswork as to where the defect is located. The high-resolution images can inform decision makers as to where to focus funding for maintenance and repairs and help predict deterioration and cost. The efficient and rapid collection of visual data has the potential to lead to modifications in the inspection cycle, making it easier—and often less costly—to conduct follow-on visual inspections.

In the future, UAS will be to be able to better map bridge-deck surfaces, especially those with high traffic counts and more than three traffic lanes. The use of UAS will minimize lane closures, but even with a single lane closure on a busy highway, it is difficult to get accurate square footage measurement of patches and potholes when the inspector is standing a few lanes away. As UAS regulations and inspection-use permissions requirements mature, UAS use will enhance inspection safety (for both inspectors and the traveling public) and accuracy of data for bridge structures by creating an accurate map of the bridge deck, enabling the inspectors to review that imagery and measure the different condition states. This accuracy could benefit the BMS process with improved data. Additionally, with an imagery history (via a photo or data) of the bridge deck, bridge owners can more accurately track deterioration rates for bridges in different locations and refine the BMS accordingly.

Utah DOT[4] is planning to try flying and imaging the undersides of bridge decks to create a map to track cracking from inspection to inspection. If this process works as desired, it could potentially be applied to other bridge elements as well, further enhancing the data entered into the BMS.

Utah DOT[5] is also exploring the development and employment of software that automatically detects cracks, potholes, and patches based on UAS-produced maps. The desire is to give inspectors (and a BMS) the condition state and quantities for each defect. This information could also lead to better data input into the 3D models developed from UAS inspections. The use of this type of software is being discussed as a means to detect cracks in other primary elements of structures. In the meantime, however, using UAS to view bearings on top of a tall bent or in other hard-to-reach areas provides inspectors with better and more accurate data in the BMS.

DATA STORAGE AND ARCHIVING

The amount of data UAS sensors are capable of collecting make the storage and archiving of the data a pivotal aspect of data management. Data must be properly reviewed and saved while the inspection team is in the field, with contingencies available should something out of the ordinary occur. Once the inspection is complete, the data need a home for near-term recall and analysis, and long-term archiving for bridge condition trending over time.

Field Storage

While in the field, UAS-captured data are typically stored onboard the UAS and can be transmitted, in many cases, from the airborne sensor to another device for additional storage and data backup. The amount of data collected will vary from project to project. Using a UAS for a large bridge inspection that takes multiple days to complete may generate more than 50 GB of data. Thus, the proper amount of available data storage in the field, both onboard the UAS and on the ground, must be planned during the preflight discussions.

Storage onboard the UAS is typically accomplished by means of an SD or MicroSD memory card. The card may be carried onboard the sensor, or the sensor may transmit data to the card via a recording device attached to the platform. Onboard storage capacity allows the inspector to store hundreds to thousands of images depending upon the resolution of the sensor and the standard COTS file format used (e.g., RAW versus JPEG). Each platform will have its own

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[4] Interview with Paul Wheeler, lead UAS coordinator and technology advancement specialist, on October 2, 2019.

[5] Interview with Paul Wheeler, lead UAS coordinator and technology advancement specialist, on October 2, 2019.

specifications as to the size of the SD/MicroSD card it can accept. The storage capacity on UAS-compatible memory cards varies greatly and may range in price from a few dollars for a 32 GB card, up to $30 for a 128 GB MicroSD card (based on the costs at the time this report was written). This cost variability can be attributed to differing write speeds. Faster memory cards allow for more data to be stored quickly but at a higher cost.

To obtain the highest-quality images, it is recommended that the images be stored onboard the platform or sensor on the recommended SD or other storage device in addition to any images that may be captured on the control station. Using memory cards with faster write speeds is recommended to ensure the quality of captured images.

Having multiple SD cards available in the field will reduce downtime between flights. Multiple storage devices allow the inspection team to swap out memory cards and download the data from one card to a laptop while another card is used during the next flight. Having multiple storage devices also reduces the risk of losing all the imagery in the event of a mishap that results in a total loss of a memory device or the UAS. A recommended practice is to store UAS data in an additional location as well, such as a removable or external computer storage device, even if the data in the field are stored using multiple memory cards or on a field laptop computer. One additional field-storage option is a standalone external hard drive that can copy the information from the SD cards without the need for a computer.

Another means to ensure inspection data are stored safely is to upload the data to a secure private network server or cloud service while in the field. Using a third-party data-storage service entails a data-streaming connection, such as a personal Wi-Fi or cellular connection. If access to such a storage option is available, this alternative has the added benefit of allowing a team member in the home office to begin postprocessing images and creating required inspection visualization and presentation products while the team is still in the field. Conducting postprocessing concurrently with the inspection may reduce overall time requirements.

Organizational Data Storage

Following each inspection, the bridge owner will store the data collected for use in analyzing inspection results and developing inspection reports. Important UAS data will then be archived for future use, such as trend analysis on bridge defects. Decisions regarding which method is used for organizational data storage are again complicated by the amount of data made available through UAS use. Cloud storage services, removable storage devices, and local server or network storage are all options for the bridge owner.

Cloud Services

Cloud services provide a relatively low-cost storage media and are becoming increasingly popular. A simple internet search reveals that cloud services, depending on the organizational structure of the user, can range in cost from a few dollars per month for an individual to more than $100 per user per month for a terabyte (TB) or more of storage (at the time this report was written). Postprocessing suites may also provide cloud-storage solutions, offering an easy means of disseminating the finished product after postprocessing. Cloud storage also allows quick access to products and information from almost any location that has an internet connection.

Cloud storage also offers the added benefit of reducing cost by reducing onsite equipment, its associated maintenance costs, and added personnel requirements. A sample cost estimate for a bridge inspection using an existing cloud-storage solution is as follows:

- 15 GB of data collected per bridge inspection.
- Cloud service subscription rate: $0.023 per GB per month; or $0.0125 per GB per month for infrequent access (IA).
- Cost of data storage: $0.345 or $0.1875 IA per bridge per month; $4.14 or $2.25 per bridge per year.

Removable Storage

Removable media storage devices, such as external hard drives, are another means of storing and archiving data. They offer large storage capacities at a relatively low cost with multiterabyte hard drives currently costing approximately $50 or more. At present, bridge owners with ongoing and maturing UAS inspection programs are opting for this storage solution as a starting point based upon its flexibility, simplicity, and cost. This option does not congest local organizational servers, transfer rates are not limited by internet connection speeds, and it can provide an effective means of backing up data.

Private or Local Servers

Private or organizational (i.e., local) servers are another option for storing imagery and inspection products. If a private server is used, it is recommended that its storage capacity be at least 10 to 20 TB and that it be expandable to accommodate additional future storage requirements.

A major downside to a private server is the cost associated with running, maintaining, and eventually upgrading the equipment, potentially costing tens of thousands of dollars in physical assets, labor hours, and power.

In interviews with several State DOTs during this research, using a locally owned server was either not desirable or not allowed by the organization due to the memory capacity required to serve the inspection needs for the entire State.

CHAPTER 8. SUPPLEMENTAL AND FUTURE TECHNOLOGIES

As more bridge owners and inspectors incorporate UAS into their processes, the UAS technologies available to improve inspections continue to advance. This chapter discusses some of the technologies that are available and being explored for use in inspections as well as developmental technologies that could be applied in the future.

FIRST PERSON VIEW

FPV devices or goggles, while not a new technology, are a relatively recent addition to the bridge inspection toolkit. FPV gives the user a unique perspective from which to view imagery and control the UAS sensor wirelessly. Some FPV systems provide HD 1080p video and allow the user to control the sensor in real time with movements of their head. The image provided has been compared to looking at an 18-ft HD TV from about 9 ft away.

Another advantage to some FPV systems is the ability to digitally magnify the image, making it appear as though the object in view were significantly closer, thus allowing a bridge inspector to see hairline cracks in the structure.

This technology, when employed effectively, can reduce the amount of image data stores by focusing on only those areas that have defects instead of collecting a large array of images that must be sorted later.

Using FPV entails one member of the team being very focused on viewing the video, possibly necessitating an additional crew member who can observe the UAS and surrounding airspace. Operating without an observer presents a potential hazard, will drive the way the inspection team is structured, and should be included in the safety plan and risk analysis prior to the inspection.

SENSOR TECHNOLOGIES IN DEVELOPMENT

The UAS sensors currently available can provide high-resolution and very detailed images that offer immense amounts of visual information. These sensors, as capable as they are, cannot provide much more than visual images of the surface of an object or detailed images of thermal variations that can identify subsurface defects.

To deliver infrastructure imagery and information beyond EO and thermal, manufacturers are developing GPR and ultrasonic sensors that can be carried onboard a UAS. These two types of sensors, like visual sensors, provide nondestructive means with which to inspect structures.

GPR relies on pulses of radio waves in different frequency ranges to penetrate the surface of a structure to different depths and then captures the reflected radio waves to provide information on what is below the surface, such as corrosion, reinforcement, and voids. This type of sensor is typically pulled on the surface by a hand or vehicle and tends to be bulky. However, research is being conducted by organizations such as the University of Massachusetts Lowell to integrate GPR sensor technology onto a UAS. At least one company has integrated a GPR with a commercial UAS platform and used the system for bathymetry, underground infrastructure inspection and geological surveys (UAS Vision 2017).

Another nondestructive inspection method being investigated for use on UAS platforms is ultrasonic sensors. The ultrasonic sensor provides the ability to acquire thickness measurements that may be used to identify levels of bridge element section loss. This advance has been tested by attaching ultrasonic testing probes to a UAS specifically designed for the purpose. The UAS maintained contact with the surface being inspected using electromagnets, and it was able to achieve the same level of accuracy as a manual inspection using hand-held sensors (Mattar and Kalai 2018).

GPR and ultrasonic sensors are two types of sensors that, at the time of this writing, were being developed and tested for infrastructure inspection using a UAS. Another technology being explored by researchers at the University of New Mexico is a UAS-mounted laser to measure both cracks as well as the deflection of rail-bridge structures when a train is transiting the bridge (Garg et al. 2020). The laser provides bridge deflection measurements within approximately 10 mm, depending upon the distance of the UAS from the bridge.

MULTISPECTRAL AND HYPERSPECTRAL IMAGING

In addition to EO and IR sensors currently in use for bridge inspections, additional UAS sensors used in other industries could prove useful for bridge inspection purposes. Multispectral and hyperspectral imaging sensors are two types of specialized sensors being examined by users of UAS for bridge inspection.

Multispectral and hyperspectral imaging combine spectroscopic and image information at the same time. This type of imaging allows the user to see subtle variations in the scene resulting from reflected and radiated energy across various wavelengths (IM Publications Open n.d.). The primary difference between hyperspectral and multispectral imaging is the number of bands of a wavelength they capture. Multispectral sensors are limited to a few wavelengths separated by spectral segments that are not measured. These sensors are used to collect data on the Earth’s reflectance. Hyperspectral sensors measure across many contiguous wavelength bands, providing more information than a multispectral sensor. Because of this capability, the hyperspectral sensor provides higher volumes of information (Shippert 2004). To draw an analogy, a multispectral sensor may be able to map a forest, where a hyperspectral sensor will be able map the species of trees in the forest (IM Publications Open n.d.).

While these sensors are used for a variety of agricultural, geological, and environmental purposes, they are not being actively employed for bridge inspections at present. There is research into use of these sensors for road infrastructure monitoring, and their capabilities and products may offer paths to the assessment of surface conditions (Herold et al. 2004). These sensors also offer the user a means to track environmental changes, determine surface geology, and identify vegetation for site planning and monitoring.

UAS PLATFORM ADVANCEMENTS

A project underway in Europe at the time of this writing included using a UAS fitted with robotic arms and computer vision capability to assist in infrastructure inspections, particularly for bridges. In the AEROBI project, or AErial RObotic System for In-Depth Bridge Inspection by Contact, the UAS is fitted with robotic arms that can conduct nondestructive evaluation of concrete for cracks, delamination, and spalling (Fehrl Knowledge Centre n.d.). The system is being designed to measure defect dimensions and automatically process them to provide structural assessments. Such a system could reduce risks for human inspectors by using flying robotics to reach hazardous areas of a bridge.

Additionally, advancements in collision avoidance systems will make semiautonomous bridge inspections more viable. Various systems are being developed based on computer vision, sonar, laser range finders, and LiDAR. All these new technologies have the potential to bring greater degrees of automation into the bridge inspection process.

USING AI IN UAS OPERATIONS

The current COTS UAS technologies typically require a pilot to control the platform and rely largely on the platform maintaining a continuous LOS to GPS satellites to ensure effective automatic position holding. In confined or restricted spaces that do not provide a clear LOS to satellite constellations, GPS-aided navigation is lost. Without a GPS downlink to the platform, it enters a mode of flight that requires the pilot to maintain horizontal position control manually instead of the platform autopilot maintaining a stable spatial position.

Manual UAS control can be challenging and result in more difficult flying conditions, potentially creating hazardous situations for the platform and personnel on the ground if the pilot is not well trained and proficient. The platform becomes more susceptible to winds, and manual corrections may be more exaggerated than those made by the platform's automatic flight controller. This movement can lead to blurred or imprecise imagery. Flying beneath the bridge deck is the most commonly encountered situation where manual control is required.

In these early stages of UAS employment for bridge inspections, the most common solution for loss of GPS signal is to ensure the UAS pilot is skilled and experienced in manual flight operations. As UAS technology advances, another option is becoming more readily available: augmenting or removing the pilot from the active control loop by using AI. UAS systems with AI technologies (e.g., simultaneous localization and mapping algorithms that would allow the UAS to navigate visually instead of relying on GPS) incorporated into the system are capable of navigating without human input other than giving instructions on when and where the UAS is supposed to fly and maintaining override capability in the event of a malfunction.

Systems that rely on computer vision, a type of AI technology, for collision avoidance are currently available. Computer vision allows the UAS to detect and recognize objects in its environment and respond in an appropriate and timely manner to avoid a collision. These systems can fly much closer to a bridge in a GPS-denied environment than an unskilled pilot can, thus providing better quality images. In one example of employing AI to enhance UAS flight operations, a company has demonstrated a system that, without human input, can fly between the girders of a steel railroad bridge while maintaining a safe clearance from the girders on either side of the platform (AutoModality 2017).

AI IN DATA ANALYSIS AND POSTPROCESSING

Other AI technological advances are in development to enhance the data-collection processes associated with UAS and to increase the speed and accuracy of imagery postprocessing. As technology advances and machine learning improves, this technology could be applied to the task of analyzing infrastructure images for specified defects. Currently, AI and machine learning systems can identify both animate and inanimate objects with high levels of accuracy and can categorize objects based on previous analysis. Such approaches can be accomplished using several different methods, but the shared goal is for the computer to be able to detect defects by learning what they look like. An example of bridge-specific research in this area was conducted by a research team using deep-learning neural networks. The team trained the computer to recognize defects in three different ways: classification, localization, and segmentation. Each required that the computer be given information relevant to the crack (Dorafshan, Thomas, and Coopsman 2018). Such a process could lead to automated, rapid identification of defects difficult to detect with the human eye.

TECHNOLOGY ADVANCES IN DATA ANALYSIS AND POSTPROCESSING

Researchers at the Michigan Technology University (MTU), in partnership with the Michigan DOT, have successfully developed and demonstrated the capability to collect EO and IR imagery of bridge decks and automatically analyze the data for defects and evaluate bridge-deck conditions. MTU researchers developed two algorithms to run on software programs that automatically analyze UAS imagery and detect spalling and delamination in bridge decks.

The MTU-developed algorithm for spall detection, known as the “Spallgorithm,” was shown to identify spalling successfully using photogrammetrically derived DEMs with a resolution and accuracy of 2 cm or less. MTU research teams also created an algorithm to identify bridge-deck delamination through the automatic analysis of IR imagery collected with UAS sensors. The algorithm uses both IR and EO imagery of the bridge surface to highlight spots on the deck that exhibit abnormally high temperatures while no visible structural alternations are present in the EO image (Brooks et al. 2018).

Advances such as these could save time during the postprocessing of UAS data, improve the accuracy of defect detection during bridge-deck inspections, and enhance the safety of the inspection teams by limiting time on the bridge deck.

CHAPTER 9. UAS INSPECTION CASE STUDIES

OVERVIEW

An effective means of reporting information, from which the bridge owner or UAS practitioner can learn, is through case studies describing the experiences of organizations with considerable practical knowledge using UAS to support their bridge inspections. As part of this study, researchers interviewed State DOT employees and contractors across the United States to learn more about their use of UAS in bridge inspections. This chapter summarizes three cases in which UAS were used in routine bridge inspections and the lessons learned from those inspections.

The first case study discusses an inspection of the Ticonic Bridge, a multilane bridge connecting Waterville and Winslow, ME. This was a routine inspection during which the Maine Department of Transportation (MaineDOT) augmented its standard inspection process with UAS to capture enhanced imagery of parts of the bridge that were very challenging to access. The inspection team considered this a seminal case given the challenges of inspecting a wide, renovated bridge over a dam and fast moving water.

The second case study covers a proof-of-concept project in Colorado in which UAS was used to inspect a small bridge in Glenwood Springs. Because this small, rural bridge presented few challenges when using traditional inspection processes, Colorado DOT (CDOT) used the inspection to explore advantages and disadvantages of using UAS.

The third case study looks at Utah DOT's early use of UAS-mounted IR sensors to inspect bridge decks on interstate highway bridges in Salt Lake City. Utah is in the early stages of testing this capability but has discovered some great benefits, as well as some challenges, to applying this new technology in their bridge-deck inspection process.

The discussion that follows reflects the experiences of the inspection teams and the UAS operators during these inspections. In each case, the UAS were used as a supplemental tool for the inspection.

CASE STUDY 1: TICONIC BRIDGE, MAINE

Background

This case discusses the routine inspection of the Ticonic Bridge performed over a 3-d period, beginning on June 22, 2017, and defines the equipment and processes used to plan and execute this UAS-aided inspection. Situated in a complex environment, this bridge illustrates how UAS techniques can be used to supplement the routine inspection of bridges that otherwise would both present a significant risk to personnel as well as create traffic delays for the local population.

In this case, the inspection team used UAS to access and capture imagery of difficult-to-reach areas of the bridge that are typically accessed using a UBIT or by other access methods, such as climbing. The inspection was performed using a combination of traditional tools and methods, including the use of a UBIT, to visually inspect and capture images of areas with known defects and to record the condition of the remainder of the structure. This inspection led the MaineDOT to conclude that future routine inspections of the bridge could be conducted first using UAS; UBIT techniques will be reserved for follow-on inspections, as needed, based on the findings.

At the time of this inspection, UAS was a relatively recent addition to the inspection toolkit. This inspection was the sixth time the contracted inspection team had employed UAS. Originally this inspection planned to use a UBIT only, but permission was given by the bridge owner to employ UAS as well. This permission allowed the inspector to explore advantages the platform-mounted sensors (in this case high-resolution digital cameras) could offer as well as enhancements to the inspection process that could be realized by using this emerging technology.

Details of the Inspection

The Ticonic Bridge is a wide bridge situated over complex terrain, both natural and artificial, making it challenging to inspect (figure 19). It is a multispan bridge comprising three adjacent bridge types. The two-steel, welded-plate and build-up riveted-girder bridge has cast-in-place concrete decks. The adjacent historic, soil-filled-spandrel, arched-rail bridge was used in the past to support rail loads but currently only supports a pedestrian sidewalk. The bridge has five traffic lanes, two westbound and three eastbound, along with the sidewalk, and spans the Kennebec River.

As previously noted, this routine inspection began on June 22, 2017, and took place over 3 d. The contracted inspection team performed the work on behalf of MaineDOT. The first 2 d of the inspection employed two inspectors and a three-person crew supporting the UBIT comprising one UBIT operator and two flaggers for traffic control.

On the third day, the inspection continued with the team leader working with a UAS pilot who had been provided by the UAS service provider to perform the flying to augment the inspection. The use of a separate sensor controller and monitor allowed the team leader to control the camera independently of UAS flight controls during the inspection.

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Figure 19. Photo. UAS aerial view of the Ticonic Bridge.

Given that this inspection was performed in the early days of UAS use by MaineDOT inspectors, the intent of the inspection team was to use the UAS to capture images of areas on the bridge originally photographed during the first 2 d while using the UBIT, and then compare the images to determine if, in fact, the UAS provided a product suitable for inspection purposes. In addition, the UAS was employed to photograph areas of the bridge not accessible using the UBIT, including the south side of the bridge. As previously stated, the south side consisted of a pedestrian walkway built upon a portion of the original soil-filled spandrel, arched-rail bridge. The geometry and condition of this portion of the bridge would not allow sufficient access to all parts of the bridge and would not support the weight of the UBIT. The bridge was too wide to allow an inspector to view underneath the south side of the bridge deck with the UBIT positioned on the north side.

UAS Platforms Employed

The inspection team conducted the flights using two professional cinematography UAS capable of carrying various sensors. The two platforms were manufactured by a major COTS UAS manufacturer.

The primary platform was modified to carry two sensors simultaneously: one bottom-mounted sensor (the standard sensor configuration for this platform) and one top-mounted and upward-facing sensor, which is what required the platform modifications. The top-mounted camera-system modifications included the following components:

- Camera bracket.
- Gimbal.
- Voltage regulator.

- Video transmission system.
- Remote control receiver.

As depicted in figure 20, the top-mounted sensor modification allowed for direct views of the underside of the bridge deck and into the small spaces between the soil-filled concrete arch and adjacent steel structure.

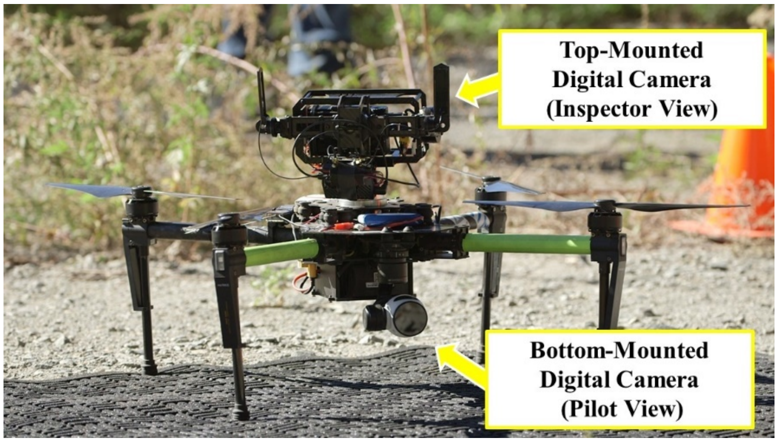

Figure 20. Photo. Primary UAS employed for the Ticonic Bridge inspection.

A second UAS model was used to capture the general aerial imagery of the bridge as well as the environment upstream and downstream of the bridge. Neither platform was equipped with external lighting, thus all bridge images were captured using the existing environmental light.

UAS Sensors Employed

The top-mounted sensor used on the primary platform was an EO sensor used to capture high-quality photos and video. The sensor captured images at 20.2 MP and could record HD video at a resolution of 1080p. The lens had both optical- and digital-zoom capabilities, allowing a magnification of 54 times for photos.

A sensor with these specifications was selected for this mission for several reasons. The sensor could be remotely controlled by the inspection crew via signals from a remote-control receiver, thus allowing the inspector to steer the camera independently of the pilot flying the platform. Additionally, the sensor offered quality low-light performance, an important criterion for imaging the underside of the bridge deck as no additional lighting systems were used on the platform. The optical zoom ability of the lens also allowed for an increased standoff distance from the bridge structure, and the small form factor (or weight) helped maximize the platform’s flying performance.

The bottom-mounted sensor on the primary platform was part of the standard equipment package that came with the platform. This sensor could capture 12.4-MP images, had a 94-degree field of view, and was could record 4K video. The bottom-mounted sensor was used by the UAS pilot only for viewing the position of the platform, not to capture any inspection imagery.

The bottom-mounted factory sensor was selected for its compatibility with the platform and the associated UAS computer application and its low weight as compared with other similar options. Additionally, its ability to be fully articulated by the pilot via the 3-axis gimbal on the underside of the platform proved beneficial in providing improved spatial awareness for the pilot.

During the UAS flights, the bridge inspector controlled the top-mounted sensor to view the bridge imagery for quality and usability as well as to identify and capture multiple photos for use in the final inspection report while the pilot controlled the UAS. This dual control was accomplished by using a separate controller to operate the sensor while the pilot focused on safe operation of the UAS. The pilot-inspector teaming model created time savings during the imagery postprocessing phase of the inspection.

UAS Flight, Imagery Capture

Since this UAS inspection was preceded by a traditional UBIT inspection, the planning for the UAS flights could leverage the findings from the first 2 d, allowing the inspection team to focus the UAS flights on areas of the bridge that were inaccessible using the UBIT and where additional images were determined to be needed to satisfy the inspection requirements.

Imagery Capture

During the UBIT inspection, the team identified areas of the bridge that could not be easily seen and were difficult to inspect adequately. The team adjusted the UAS flight plan to cover those specific areas of the bridge. As it turned out, the areas planned for UAS imaging, particularly the spaces between the spandrel arches and the steel-girder sections, were extremely difficult to access via any other means, and thus high-quality imagery of the spaces did not exist prior to this UAS-augmented inspection.

Flight Clearances

An important part of the UAS planning process involves ensuring the inspection team receives the necessary flight clearances from the local aviation authority. The location of this bridge was more than 5 mi away from any existing airport, no other airspace restrictions were active in the vicinity of the planned flights, and the environment allowed for the platform to remain within the pilot's LOS. Therefore, no special FAA waivers or certificates of authorization were necessary. The only requirement that had to be met was for the pilot to be certificated under 14 CFR 107 as a certificated remote pilot (14 CFR 107 2016).

Because one of the bridge piers connects to a concrete dam, the inspection team spoke with MaineDOT and the dam operator to gain access to the entire bridge–dam complex during the inspection. Coordination with property owners and local agencies was an important part of the planning process as the UAS pilot and inspector needed to walk out onto the dam to ensure the UAS could be seen during certain times when the platform was underneath the bridge deck.

The degraded structural condition of the spandrel arches was another identified hazard that prevented the use of the UBIT on the south side of the bridge. These poor structural conditions made access to certain areas underneath the bridge deck impossible to inspect at a close range either by using a UBIT (due to the width of the bridge) or by boat (due to the hazardous conditions presented by the dam and swiftly running water underneath the bridge). Thus, the UAS provided a means to view these sections of the bridge at a reduced level of risk to the inspectors compared with other access methods.

UAS Flight and Inspection Execution: Successes and Challenges

On the day of the flights, the team had additional time to fly areas of the bridge previously covered by the UBIT. The time available for the additional imaging was a result of the short period required to capture the specific, planned views for the UAS. The inspection team decided to overlap some of the UAS imagery with that taken using the UBIT for comparison purposes and for use during future inspections.

As discussed, the team focused its efforts on areas of the bridge that were not previously observed during the UBIT inspection. During future inspections, the bridge owner plans to add more flights and plans to capture additional video to document the entire bridge condition as well as the status of specific areas of interest.

The modification to add the top-mounted camera system put the platform very close to the maximum takeoff weight, which greatly reduced the available flight time. At the time of this inspection, the system batteries afforded the team 10 to 12 min of flight time in the prevailing environmental conditions. This flight time was typical given the battery technology available, the weight of the UAS, and the safety margin built into the flight plan. The available battery life would have decreased with higher winds, gusty conditions, or cold temperatures.

Nine flights were needed to capture the desired bridge imagery. The time needed for battery switches between flights was about 5 min. The inspection team used this time to debrief the previous flight and its results and to modify the plan for the next flight if changes were determined to be necessary.

Most of the flying was done at midday, and the high-sun conditions created some flight challenges for the inspection team. On several occasions, the bright sky in the frame of the image caused the camera’s auto focus to struggle and required the team to make multiple changes to the aperture setting to obtain quality images. The team positioned the UAS so that consistent lighting filled the frame and adjusted the camera settings for each flight to optimize the lighting conditions anticipated for the next area of the bridge to be imaged. The sensors used required the aperture (or ISO settings) to be adjusted manually between flights. Today’s newer technologies are more advanced, so the camera operator can adjust settings from the controller while the platform is in flight. The primary area of interest for imaging by the UAS was very dark (figure 21). This area between the historic, soil-filled concrete arch and adjacent steel structure was approximately 8-ft deep (measured vertically). Several flights were needed to refine the camera settings enough to obtain quality images.

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Figure 21. Photo. Key area of interest for UAS imaging.

The ability of the top-mounted camera to capture images in a RAW file format was very important for this inspection. During the inspection, the team needed to constantly review the photos and significantly adjust the camera's exposure settings to see details and verify image content and quality. The additional data available in a RAW image allowed for advanced image viewing and refinement while in the field.

The platform used did not have an external lighting capability. For future inspections of this and other bridges, the team intends to use a more advanced system that has an LED lighting capability to provide artificial illumination to dark areas under similar bridge decks.

An additional challenge to flying a UAS around this bridge, as with many bridges, was the loss of GPS signal to the platform when flying under the bridge deck. Fortunately, the pilot for this inspection had considerable UAS flight experience and was skilled with manual flight control. Newer UAS technologies are now available that provide enhanced internal navigation capabilities to ensure platform stability when GPS signals are blocked.

UAS Data Management and Postprocessing

Imaging a bridge using a UAS can generate a large amount of data, and the Ticonic Bridge was no exception. Even with the UAS focused on areas of the bridge not reachable using the UBIT, the inspection team captured more than 26 GB of video and photo data during the nine flights. No data were deleted during the inspection or post inspection; it was stored on multiple SD cards and transferred to a hard drive.

The inspection team worked to manage the amount of data collected by having the inspector review the video feed from the platform in real time, directing the pilot toward areas of interest, and taking note of key images captured during the flight. The inspection team leader reviewed all the images and video captured the day of the inspection. During the reviews, the team leader looked for the images that best represented the bridge's overall condition as well as those that depicted any significant deficiencies.

During this inspection, reviews of the imagery files took place in between flights while the platform batteries were replaced. During the field review, the inspector viewed the photos and video captured by the UAS directly from the SD memory card carried within the sensor. The SD card was read on a laptop computer with an HD monitor in a simulated office environment: in this case, the darkened cab of the team's truck.

Once the inspection team leader was satisfied with the subject and quality of the desired images, they were designated for use in the inspection report. The selected images were reviewed again during the inspection report completion process, with the Team Leader performing all postprocessing. The images that best represented the structure and its condition were included in the final report. If the photos selected and saved did not completely satisfy the inspection needs, the inspection team was able to review the 4K video captured by the UAS sensor and extract additional images for the report from the video.

With the needed images selected, the photo files were compressed to meet client needs and any requirements for inclusion in the final inspection report. All images were formatted as JPG files. The size of the original image files was generally 23 MB each. These were compressed to 13 MB, which provided a satisfactory resolution while minimizing the memory demands on the database. The 13-MB image files were also deemed adequate for online review and for printing the report.

The images selected for use in the final inspection report were then input into the inspection and maintenance software used by MaineDOT. This software solution was used to create a document for inclusion in the NBI. While the software can accept video, the bridge owner requested that only photos be included in the report to limit the amount of data transferred. All images and video were delivered to MaineDOT on a portable memory device and archived on the client's network once the project was complete.

Inspection Report UAS Images

The images of the Ticonic Bridge used in the inspection report submitted to the MaineDOT ranged from downstream photos depicting the general condition of the bridge from a distance to close-up images of the underside of the bridge deck—areas either inaccessible using a UBIT or hazardous to view due to the need to enter moving water.

The following imagery examples illustrate some of the capabilities of the UAS used for this inspection. The images that follow do not come close to representing the quality or resolution of the images saved to the internal UAS memory cards and do not represent the full zoom capabilities of the UAS sensors.

While standing in a single spot on the bank of the river, the pilot and inspector could view the bridge from a distance to get an overall view of the condition of the piers and spans and the underside of the bridge deck where the UBIT could not reach (figure 22 and figure 23, respectively).


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Figure 22. Photo. UAS-captured downstream view of pier and spalled concrete hanging from span.


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Figure 23. Photo. Typical underside view of concrete arch, inaccessible using a UBIT for imaging.

Positioning the UAS below the bridge deck was more challenging for the pilot due to the loss of GPS signals to the platform, but the ability to image the spaces between the concrete arches and the steel girders using the top-mounted, upward-facing camera gave the inspector unique views of the bridge that had not been adequately imaged previously using other access methods (figure 24).

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Figure 24. Photo. Image of the underside of concrete arch between the steel girders using an upward facing camera on the UAS.

Advantages Realized Using UAS

For the routine inspection of the Ticonic Bridge, there were distinct advantages to using UAS. The most important was managing safety risks during the inspection, including the ability to access areas of the bridge unreachable by UBIT and hazardous to view from the water directly below the spandrel arches.

Additionally, the UAS was able to image the entire bridge structure without flying directly over the traffic lanes by offsetting the platform to the side when inspectors needed overhead imagery.

When the UAS was operating, there was no need for lane closures and no need for flaggers standing in traffic. This approach to a routine inspection eliminated traffic delays to the traveling public. Using UAS also eliminated the safety concerns when using UBIT, including exposing traffic control personnel to heavy traffic conditions and requiring an inspector to suspend off the side of the bridge. It also eliminated the need to attempt to take clear photos from the turbulent water below.

Using the UAS mitigated or eliminated additional safety risks identified during inspection planning: working on steep slopes, uneven working areas, deteriorating structural materials, and working near vertical drops.

Following the inspection, it was determined that the inspection could have been entirely performed using UAS as a substitute for the UBIT.

Conclusions

The routine inspection of the Ticonic Bridge in Maine demonstrated the viability of integrating UAS into the bridge inspection process for a complex bridge structure, providing a means to view and capture images of areas of the bridge structure inaccessible by UBIT.

Integrating UAS into the inspection process provided the inspector key advantages, including having the ability to capture images of areas under the south side of the wide bridge deck between the steel girders and the deteriorating spandrel arches. Using the UAS, the inspector was able to view and identify bridge-structure discrepancies at a close range in a way that satisfied the requirements of a routine inspection. The images captured by the UAS were of high quality, allowed the inspector to accurately evaluate the condition of the bridge, and were more than suitable for inclusion in the final inspection report submitted to MaineDOT.

The UAS also mitigated several safety hazards, including minimizing disruptions of traffic when inspecting the south side of the bridge, eliminating the need for the inspector to be positioned below the south side of the bridge on the dam or in the water, and minimizing exposure of personnel to deteriorating concrete and dust.

Based on the results of this integrated inspection, the contracted inspection team and the MaineDOT determined that, for future inspections on the Ticonic Bridge, inspections will be conducted using UAS assets to begin with, and use of a UBIT will be limited to only as needed. This approach will decrease the time required to complete the inspection, lower the costs of inspection equipment, and reduce the personnel needs for UBIT and traffic control assets.

CASE STUDY 2: GLENWOOD SPRINGS BRIDGE, COLORADO

Background

This case study reviews a UAS proof-of-concept inspection project on a bridge in Garfield County, Colorado. The inspection was conducted to examine the feasibility of using photogrammetric techniques to create a mesh that would form a 3D model of the bridge for future reference and comparison during follow-on inspections.

A small bridge near Glenwood Springs, CO, was selected for this UAS proof-of-concept study as it had intricate features associated with its steel structural members (i.e., beams, braces, bolts, plates, and multiple faces) that offered some challenges for inspectors to access. Along with a lack of surface features on the relatively new steel, this created impediments to stitching the images together during postprocessing.

Overall, the impression of CDOT and the consultants was positive regarding the future use of UAS. CDOT saw value in the data that were provided by the UAS and noted that any efficiency would be beneficial in completing a significant percentage of the approximately 4,500 bridge inspections that must be conducted annually. The consultants identified the potential to lower cost to the public by reducing the need to employ traffic management and traditional access methods like UBITs. UAS would also allow the engineer to focus on the higher-risk, higher-traffic areas.

However, for this particular bridge and similar bridge structures, the advantages of using UAS were not significant enough to warrant replacing traditional inspection methods on a regular basis. The size of the bridge and its steel structural members made using traditional inspection methods viable. By contrast, processing large numbers of images captured by the UAS would have required significant additional time.

Glenwood Springs Bridge

The bridge is located on Route 134 approximately 5.5 mi to the west of Glenwood Springs, CO, and is situated over the Colorado River connecting the north and south banks with I-70. It features a footpath to the north, a rail line to the south, and a footbridge to the east. Figure 25 shows the geography of the surrounding area. The bridge has a concrete deck and is a three-span, steel-girder bridge. It is approximately 248 ft long and is supported by two piers (figure 26).

The proof-of-concept inspection was conducted between 10:27 a.m. and 1:04 p.m. on 25 April, 2018. The inspection team included contracted personnel; a CDOT bridge inspection engineer and a representative from Garfield County were also present.

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Figure 25. Photo. Glenwood Springs Bridge overview shot.

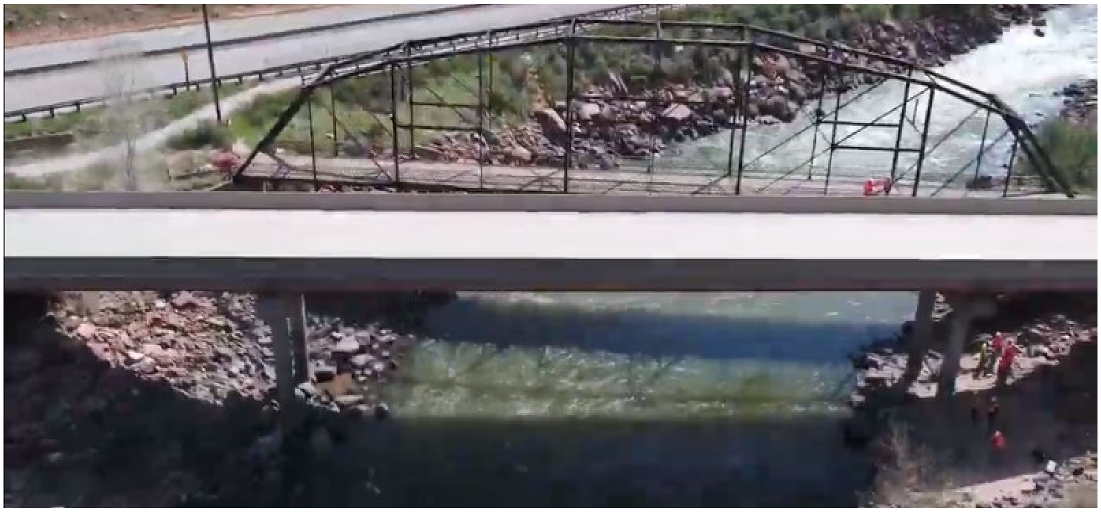

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Figure 26. Photo. Glenwood Springs Bridge from the UAS.

Commercial UAS pilots conducted the flights using a professional cinematography and inspection UAS, with a variety of UAS sensors available for carry by the UAS. The engineers on site recorded the flight path then viewed the imagery for quality and usability after the flight landed.

During a routine inspection of this bridge using traditional techniques and equipment, a UBIT is typically used, along with hand-held cameras, and traffic control is implemented to ensure safety. These traditional techniques require significant planning and would take many personnel hours.

UAS Platforms Employed

The platform employed for this proof-of-concept study was a COTS quad-rotor system (figure 27). The system was purposely built for infrastructure inspections, with mounts for gimbals on the top and bottom of the platform.

Figure 27. Photo. Inspection UAS used during the proof-of-concept study.

The UAS weighed 9.5 lb without a camera, approximately 10.5 lb with an EO camera, and 10.1 lb with an IR camera. The maximum payload capacity of the UAS was 5.16 lb.

The platform had an advertised endurance of approximately 27 min without payloads. This time was reduced to 15–17 min with a payload and to allow fora 30-percent battery reserve. The 15- to 17-min endurance time was used for planning purposes, since without a payload the UAS serves no inspection purpose.

UAS Sensors Employed

Two sensors were used on the primary inspection UAS: an IR sensor and an EO camera (referred to as camera 1 hereafter) that could be mounted in multiple positions on the UAS.

The IR sensor supplemented the inspection and was used to collect images of the bridge deck, piers, and abutment. The IR camera specifications were as follows:

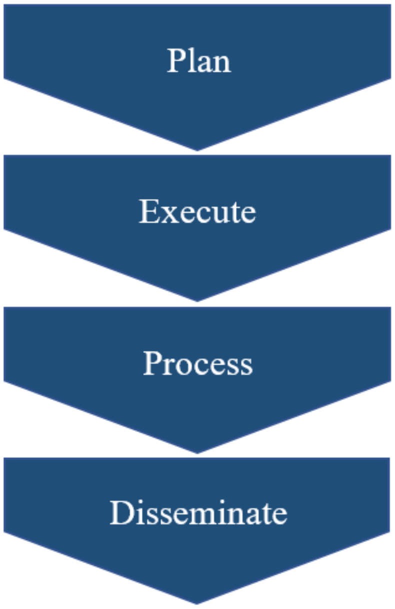
- 640 x 512 pixels.
- 30 frames per s.
- 13 mm lens.
- Operating temperature range of 14 to 104°F (−10 to 40 °C).
- Scene range (high gain) of −13 to 275°F (−25 to 135 °C).

Camera 1 was the primary inspection sensor. It was a micro 4/3 camera, with 20.8-MP resolution, and could be mounted on the top or bottom of the UAS, which facilitated inspecting the underside of the bridge. When mounted on the top of the UAS, the camera was effectively used to collect imagery of the superstructure components (e.g., stringers, beams, diaphragms, underside of deck). When the camera was mounted on the bottom, it reduced the effectiveness of the camera for inspection due to the limit of 30 degrees tilt up.

Top-mounting the camera did change the center of gravity (CG) of the platform, but had minimal effect on overall flight characteristics. The CG shift from bottom- to top-mounted cameras was easily handled by the UAS flight controller, so the change in feel to the pilot is minimal. In high winds, the top-mounted camera tends to make the UAS more susceptible to gusts, but again, very minimally in this case.

UAS Flight and Imagery Capture

Like any bridge inspection, this proof-of-concept study followed a defined workflow to increase the efficiency and accuracy of the inspection and to reduce costs in both time and money. Figure 28 shows the workflow that was used.



Source: FHWA.

Figure 28. Inspection workflow.

Every bridge connection point was documented in an organized fashion with video and photos. A similar flight plan was followed to document the deck panels followed by bearings, piers, and abutments. After these elements were captured, deck EO and IR scans were made from above and off to the side of the bridge.

The original UAS inspection scope (or shot list), used during the execution phase to ensure accurate and efficient collection of bridge imagery, was as follows[6]:

- A slow pan along the full length of the exterior edge of deck. The UAV will be positioned slightly below the level of the deck so that both the exterior face of the barrier or curb and the underside of the deck overhang are visible. Photographs will be taken at 5-ft intervals, and each location will overlap with the previous location photographed.

- A slow pan along the full length of both vertical faces of each girder. For interior girders, the UAS can be positioned slightly below the bottom flange of the girders with the camera oriented up so that the full height of the girder web and top flange are visible, with only a minimal amount of the bottom of the web obscured by the bottom flange. Photographs will be taken at 5-ft intervals, and each location will overlap with the previous location photographed.

- A slow pan along the full length of the deck underside in each interior bay. Photographs will be taken at 5-ft intervals and each location will overlap with the previous location photographed.

- A slow pan along the full length of the underside of each girder bottom flange. Photographs will be taken at 5-ft intervals and each location will overlap with the previous location photographed.

- A slow pan of all visible vertical surfaces, i.e., all faces, of pier seats, caps, and shafts. Photographs will be taken at 5-ft intervals and each location will overlap with the previous location photographed.

- High resolution still images of each bearing will also be acquired. At each bearing a minimum of two images showing the faces and sides of each bearing will be captured to show as much detail as possible.

The purpose of this method was to have enough overlap (80 percent or greater) to attempt to build a photogrammetric 3D model of the structure.

Postprocessing

The images collected were saved as JPEG, DNG, and R-JPEG file types. These images were used to create a photogrammetric point cloud and mesh as well as thermal and RGB orthomosaic images of the top side of deck. The images were processed using commercial postprocessing software for photogrammetry, and basic photo editing software was used for color and exposure correction.

As part of this research and proof-of-concept project, the team wanted to examine the feasibility of using photogrammetric techniques to create a 3D mesh of the structures for “virtual inspection” purposes. It was determined that structures with intricate features (e.g., beams,

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[6] Information in this section was gathered during discussions with project team members that performed the inspection.

braces, bolts, plates, and so on) and many faces are more difficult to stitch together than structures that have more basic geometry, such as a concrete bridge. Adding to the challenge was a lack of surface features on the relatively new steel. Concrete has more variations in surface texture, which aids in the stitching process. Due to a combination of these factors as well as inadequate geotagging data quality, the 3D model was not usable, leaving just the video and photos for use in creating inspection products.

UAS Flight and Inspection Execution: Successes and Challenges

Overall, the UAS was effective in collecting high-quality imagery usable for an inspector to make determinations of whether to inspect further with hands-on or physical techniques.

For this proof-of-concept inspection, engineers had no ability to view the video feed in real time. It was determined that the method for viewing UAS imagery in the field should be settled upon prior to conducting an inspection. The method of viewing will impact how the team is organized during the flights. The team reviewed the imagery of the bridge after each flight was completed while the UAS batteries were changed. They also concluded that employing a UAS without a separate means to view real-time imagery by the inspector will lead to delays in identifying defects and areas that need further inspection.

The Glenwood Springs Bridge presented environmental challenges to operating the UAS and capturing quality imagery (figure 29). The bridge is in a valley that can funnel winds across and under the structure, and high, gusty winds were experienced during the flights. Winds compounded the flying challenges resulting from the loss of GPS signals under the bridge deck and the extensive level of imagery overlap required by the project scope.

Figure 29. Photo. Glenwood Springs Bridge UAS operational environment.

Low light and turbulent conditions under the bridge deck made getting quality images difficult: turbulence made getting close to the structure to collect images problematic, while the poor

GPS-signal reception resulted in inaccurate or degraded geotagging. The low-light conditions resulted in images requiring corrections during postprocessing.

Another issue that had to be addressed was the presence of nesting birds in the structure. Vigilance was required to avoid aerial collisions that could have damaged the platform and injured the birds. The presence of birds is of particular concern when birds of prey are nesting in the area as they can become territorial and aggressive toward UAS.

An adjacent rail bridge also restricted the flight path upstream due to its proximity to the road bridge being inspected.

Costs and Time Requirements

The total time for the inspection with the UAS was approximately 2.5 h. The UAS cost was $90/h, and the rate for the pilot was $125/h, putting the cost of the UAS team augmenting the inspection at approximately $537, and not counting the cost of inspectors and report development, which were required regardless.

Postprocessing of the imagery took approximately 32 h. No specific costs were included for the postprocessing, but this was a considerable amount of time taken up by postprocessing the large number of images and would likely increase the cost considerably. It should be noted that this time included creating a 3D model that would not be necessary for most routine inspections.

Conclusions

This proof-of-concept study showed that, while UAS can supplement an inspector's toolbox, the bridge owner and inspector will have to determine if a UAS is appropriate for the inspection of a bridge of this type. In the case of the bridge in this proof-of-concept project, it was determined that the use of a UAS did not save significantly on the time required to inspect the bridge, and the cost savings were not enough to warrant UAS being used on a regular basis to perform routine inspections. Additionally, the UAS imagery captured did not provide the results desired by the bridge owner for the steel structural members, regardless of photo quality.

Given that the bridge was new, that the structural members were not difficult to access, and the limited traffic crossing the bridge, it was determined that the desired results could have been achieved by traditional inspection methods, such as using binoculars, hand-held cameras with a zoom capability, and ladders. Thus, while the UAS provided HD imagery of areas of the bridge in a way that saved time and reduced risk, the CDOT team left with the view that the decision to use UAS was best done on a bridge-by-bridge basis.

The general conclusions for the UAS inspection in Glenwood Springs were as follows:

- UAS can be used to supplement the inspection of a steel bridge.
- UAS may be better suited for concrete bridges or bridge constructions that are not as restrictive to UAS navigation.

- Costs to the public can be decreased because UAS-based inspections eliminate or reduce the need for traffic control and a UBIT.

- Images from a UAS can be used for accurate modeling of a structure, for tracking defects, and setting a baseline for comparing subsequent inspection. Steel bridge components present a challenge due their intricate architecture. Because of this, the images taken during this study would be useful to track deterioration but not in creating a 3D model.

- Inspection using a UAS was not found to add significant value in this specific case. However, with the proper project scope (i.e., inspecting without collecting data for a 3D model), the use of UAS for this inspection may have been more successful.

- UAS may allow engineers to focus more quickly on higher risk areas or areas identified as needing a hands-on inspection.

The inspection team also concluded that there were unique issues related to this specific bridge type. Accessing the bays in a steel construction bridge is problematic with current UAS sensor technology because, due to the inability of the UAS to move within a reasonable proximity of the area to be inspected, it's not possible to collect images of a high enough quality to visually inspect weld lines.

CASE STUDY 3: USING UAS WITH IR SENSORS TO ASSESS BRIDGE DECKS IN UTAH

Background

An emerging use of UAS is employing platforms carrying IR sensors for the purpose of detecting and assessing concrete bridge decks for defects. While this application is in the proof-of-concept and testing phase, the Utah Department of Transportation (UDOT) has explored this UAS mission with multiple sensors and discovered some best practices that can enhance the results.

UDOT's proof-of-concept inspections to date focus on the use of IR cameras for inspecting concrete surfaces for delamination and other defects. The agency has explored this use on multiple bridges in the state. A six-lane, divided highway bridge on I-80 in downtown Salt Lake City is used as an example for this case discussion. This bridge is on a major route through the city. Using UAS for inspection purposes benefits the inspection team and the public by minimizing the disruption of the continuous traffic that transits the bridge daily (figure 30).

The IR inspection was conducted while previously scheduled work was being performed on the bridge, so traffic control was already in place; however, traffic control measures would not have been required for the UAS inspection only. Even when traffic control is in place, to ensure safety of flight for the UAS and the traveling public, it may be necessary to fly with a lateral offset from the bridge, collecting oblique imagery to make sure that the UAS does not overfly any vehicles. This offset flying technique may require multiple passes to ensure the accuracy of the oblique images. While use of the IR cameras on UAS are still in the exploration and learning phase, the imagery captured produced usable results for inspection-reporting purposes. When an IR camera of sufficient quality is used, the inspector can identify delamination that would normally require sounding, chain drag, or handheld IR cameras, all of which require traffic control.

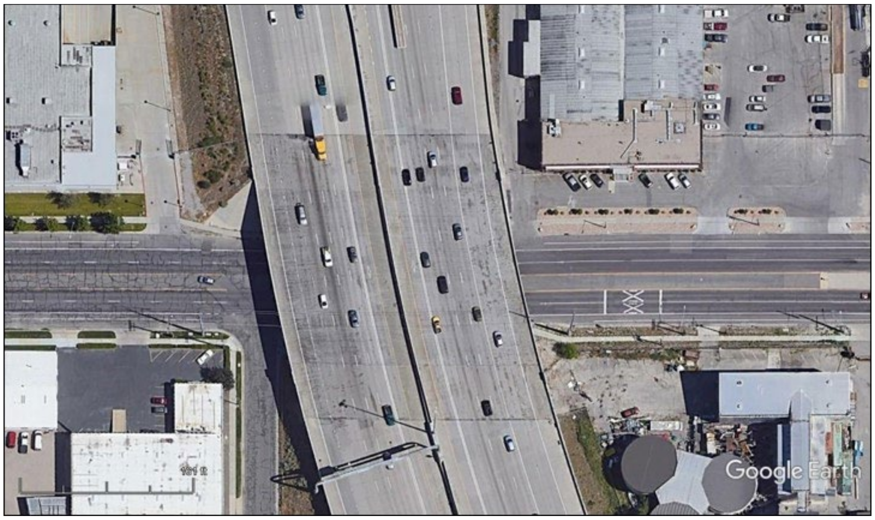

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Figure 30. Photo. Interstate bridge in Salt Lake City, UT, selected for proof-of-concept inspection.

As might be expected, UDOT's use of two different IR cameras of different technological generations delivered different results. The first UAS system carried integrated IR and EO sensors and overlaid an IR image atop an EO image (figure 31). This IR camera's low resolution did not capture defects at a quality that was consistently useful for detecting and identifying concrete delamination on the bridge deck. The arrows labeled 1 and 2 indicate areas of possible delamination.

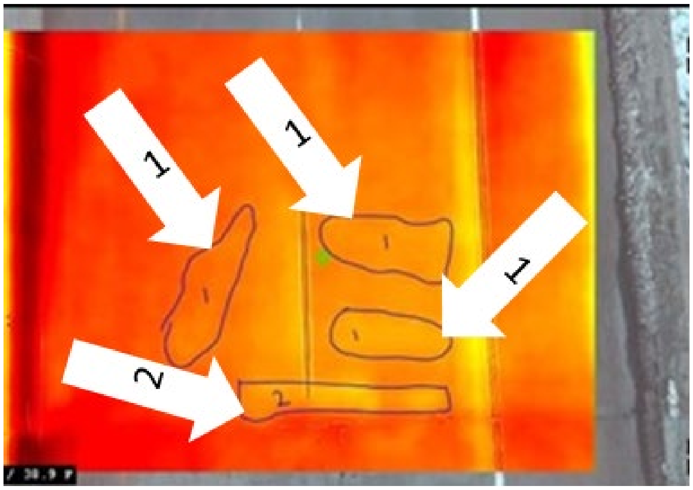

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Figure 31. Photo. EO image with IR overlay.

In the second UAS system, the IR sensor used had significantly higher resolution and allowed the inspector to identify areas of delamination that would not have been visible using the first camera. Using the advanced camera, the inspector in one instance was able to identify an area of delamination that had been missed using traditional inspection techniques (figure 32). This previously undiscovered delamination was verified by an inspector subsequently sounding the area using traditional inspection methods.

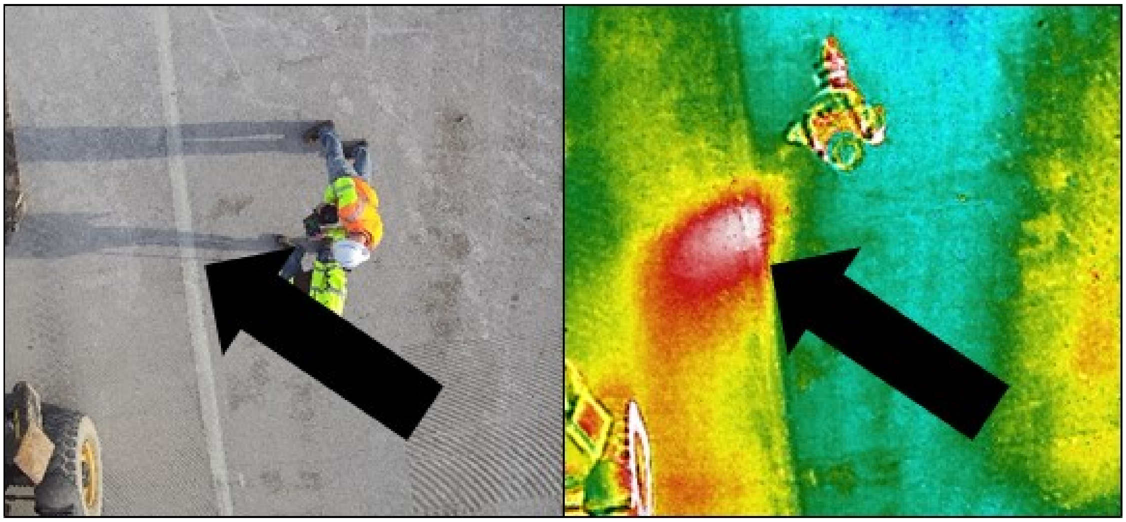

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Figure 32. Photo. EO and IR images showing location of previously undetected delamination.

In addition to the practice of deploying an advanced UAS carrying both an IR and an EO sensor, UDOT discovered other operational techniques that ensure the quality and usability of the imagery. These techniques center around controlling the environmental conditions and impacts on the concrete surface to accentuate temperature differences that the sensors detect.

Regardless of the quality of the system used, conducting the UAS flights at or very near dawn or dusk aids in capturing quality imagery. The higher the sun is in the sky, the more uniformly heated the surface and surroundings will be. The IR sensor detects differences in temperatures of surfaces and the surrounding areas. The bridge structures maintain heat longer than the air, and different densities of the materials cool or heat at different rates. Figure 33, which shows a stringer below the bridge deck, is an example of the temperature differences a high-quality IR system can capture. Capturing the imagery close to dawn or dusk accentuates these differences and enhances the quality of the image.

Another lesson learned by the Utah team was to ensure the bridge is as free of debris and equipment as possible. Anything creating a shadow, insulating areas of the bridge deck, covering the pavement, or moving on the pavement (e.g., equipment) will create temperature differences detectable by the sensor and result in false positives. UDOT learned that, with the use of higher quality IR sensors, the images do not seem to be impacted greatly by normal traffic on the bridge.

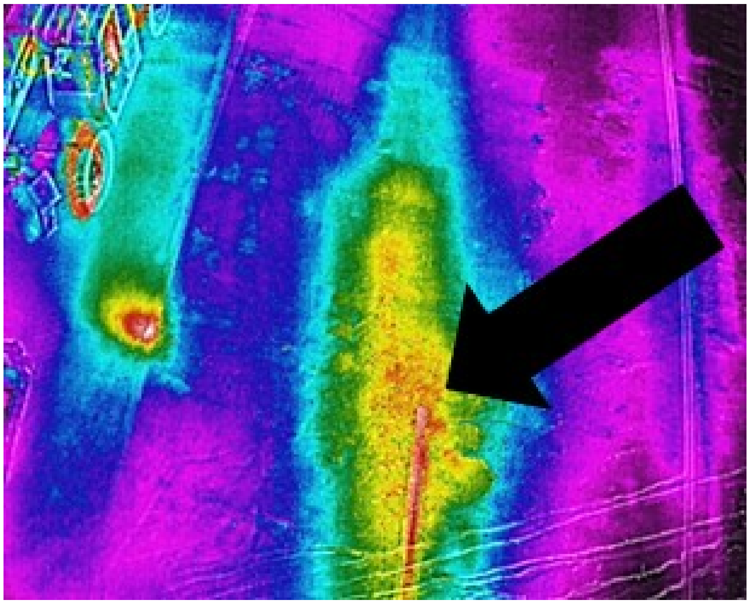

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Figure 33. Photo. IR image of stringer below the bridge deck.

Even though UDOT is in the early stages of its use of IR, the results have shown how a UAS can assist in identifying concrete delamination. However, the IR sensor will only help the inspector focus in on areas where they can see delamination; sounding or other techniques will still be required to properly confirm the extent of the delamination. Going forward, UDOT's process will include creating a database of IR images that can be used as a lifecycle tool to assist in determining how the surface is deteriorating.

At this point, UAS-mounted IR cameras are still being investigated as to their viability for this type of inspection work. The results have been mixed so far and will require further investigation to determine how they can best be applied. To better optimize the capabilities of UAS-carried IR sensors, the UDOT is considering sending members of their team through photogrammetry education courses to learn in greater detail about the capabilities of IR imagery and postprocessing analysis of the products produced.

Conclusions

The three case studies presented illustrate many of the advantages and challenges that come with using a UAS for bridge inspections. They show how the EO and IR cameras were employed for data collection on three bridges and their outcomes. The three bridges inspected encompassed both steel and concrete elements and showed the sensor capabilities on different construction materials. Each bridge had unique challenges to overcome, and the UAS brought many advantages.

Among the challenges experienced was positioning of the flight crew to ensure that LOS could be maintained. Maintaining LOS was particularly important with the complex terrain at the Ticonic Bridge site. Other challenges included managing battery life and operating under variable lighting conditions.

The loss of a GPS signal, which can lead to less stable flight operation, was encountered when flying under the Ticonic Bridge deck and around the Glenwood Springs Bridge due to the topography surrounding it. This condition causes inaccuracies in position data, which then causes problems with image geotagging. This loss of data makes using the images to create accurate 3D models less viable.

Although not currently authorized by the FHWA as practice, UAS IR cameras have the potential to detect delamination without having to physically inspect the entire surface. A potential challenge to be overcome for this application is that obtaining high-quality IR imagery requires that flights be conducted very near dawn and dusk. In large metropolitan areas, these times of day typically coincide with high volumes of traffic.

The primary advantage of using a UAS in these cases was in managing safety risk. By employing the UAS to access areas of the bridges that would typically require an inspector to use a UBIT, climbing gear, or a boat to visually inspect, the overall risk to personnel was reduced. Another area where UAS proved to be advantageous was in reducing or removing the need for traffic control. The reduction of traffic control decreased the impact of delays and improved safety for the traveling public.

Cost saving was another advantage; however, savings will be dependent on several factors, including the type of bridge, inspection to be performed, and whether a contractor is used, to name a few. These factors make properly scoping the bridge project important to ensure that each individual bridge is a good candidate for UAS inspection. Table 7 illustrates some of the advantages presented in the case studies.

Table 7. Case study UAS advantages realized.

Case Study	Access	Cost	Time	Safety	Traffic Control	Task Completion
Maine	Y	Y	Y	Y	Y	Y
Colorado	Y	N/A	Y	Y	N/A	N
Utah	Y	N/A	N/A	Y	N/A	Y

CHAPTER 10. SENSOR PARAMETER TESTING AND RESULTS

The previous chapters discussed the particulars of a UAS, what it brings to the bridge owner and inspector as a tool, and ideas for managing its operation and the data the system can collect. This chapter discusses the testing that explored the general technical aspects, internal camera settings, and information generated by the UAS and camera combination that can be used to improve results during a UAS-supplemented bridge inspection. It begins with the methodology and results of test flights performed in the field to examine the technical aspects of the sensors and platform currently being used by bridge inspection teams. The discussion then turns to the series of controlled-environment tests performed in a laboratory setting at the University of Maine to validate the field findings and to refine UAS sensor and operational parameters to provide usable recommendations for inspection teams.

The testing aimed to accomplish the following general objectives:

- Identify minimum requirements for the specification of visual sensors, cameras, or both carried by UAS.
- Determine required UAS navigation and localization tools necessary for operation around bridges.
- Specify the necessary clearance (i.e., standoff distance) between the UAS and the area of interest on the bridge to ensure quality imagery and safety of flight.
- Determine lighting requirements to ensure imagery quality that satisfies inspection requirements.

OVERVIEW OF THE TESTING.

The testing was conducted in two parts. The first part involved using UAS to inspect bridges in the field environment. Four bridges in Maine were selected. Visual inspections using UAS carrying EO sensors were performed at these locations; two inspections were considered fracture critical inspections and two were routine inspections. Although fracture critical inspections require a hands-on inspection, which cannot be performed by a UAS, the capability of the sensors to provide information that will identify fatigue cracks and other defects was tested. These bridges were selected for the complexity of the structures and the surrounding terrain, which together made them difficult to access during an inspection.

The parameters explored in the field were those that can be controlled by the bridge inspection team and included time of day, artificial lighting, image quality, and platform positioning. The factors that could not be controlled by the inspection team were mitigated to the greatest degree possible. Those factors were the current sky condition, ambient lighting, electromagnetic interference, and weather—specifically, wind.

The inspections were conducted using three different UAS and cameras from each of the following categories: consumer, professional, and commercial, as defined previously in chapter 3. Two UAS had integral sensors and one UAS was modular, meaning that the sensor could be removed and replaced with a different sensor. Additionally, the modular UAS was equipped with a gimbal mount on the top of the platform.

Each inspection was conducted to identify new defects or evaluate existing defects to determine the usability of the UAS images for inspection purposes. Multiple images of defects were captured with each camera using different settings and, when possible, different magnification levels.

Part two of the testing was conducted in a laboratory setting with a controlled environment. The goals of the controlled-environment testing included refining the results obtained in the field and making determinations on the recommended minimum system requirements, sensor settings, and standoff distances for UAS used for bridge inspections.

PART 1: FIELD-INSPECTION TESTS

The field tests were conducted on four bridges in Maine, each with known defects that could be imaged to determine the flight and sensor setting parameters necessary to capture acceptable images while also testing the ability to identify new defects. Two of the bridges required routine inspections, and two were designated as requiring fracture critical inspections. Each series of inspection images was taken at varying distances, lighting, and ISO settings under field conditions. The bridges inspected included the following:

- Veterans Remembrance Bridge in Bangor (routine).
- Sagadahoc Bridge in Bath (routine).
- Max L. Wilder Bridge in Arrowsic (fracture critical).
- Coos Canyon Bridge in Byron (fracture critical).

These bridges offered a variety of bridge structure complexities, difficult to access areas, and surrounding terrain challenges, making UAS a potentially valuable tool.

The discussions on each particular bridge highlight key findings and comparisons between the UAS inspections and inspection performed previously using traditional techniques.

The testing team consisted of a certificated bridge inspection team leader, a UAS pilot certificated under 14 CFR 107, and a safety observer who was also a certificated UAS pilot (14 CFR 107 2016). The UAS pilot was highly skilled and experienced. The images displayed were taken at a distance from the bridge that the team determined was achievable and safe by a pilot with basic flight training. It is possible to achieve closer distances, but as the distance is reduced between the UAS and the structure, the risk to the UAS is increased. While the abilities of the team's UAS pilot allowed for the capture of imagery from closer ranges, an important consideration during the field tests was anticipating the ability of a less experienced pilot to fly with GPS signals denied while the UAS is underneath the bridge structure.

Operational Considerations

During the planning and execution of the field test flights, the following operational considerations were addressed and accounted for:

- *Weather*. Before each flight, the weather at the bridge site was checked and documented using a handheld anemometer and visual observation. The anemometer was used to determine the wind speed and temperature. The winds during the inspections were generally light, from 2–3 mph, with maximum winds reaching 10–13 mph. The UAS pilot's observation was used to determine the sky condition and visibility.

- *Structure complexity*. The complexity of the structure was evaluated to determine the best approach to flying the UAS as close to the structure as possible to collect images of defects. The Max L. Wilder Bridge was the most complex of the four bridges examined due to the steel structure and the electric lines and guy-wire near the bridge. These factors required the pilot to maintain vertical and horizontal standoff from the electrical lines and to maneuver around the guy-wire.

- *Regulatory factors*. All rules delineated under 14 CFR 107 were followed, and no waivers were required to conduct the flights (14 CFR 107 2016).

- *Airspace*. The airspace above and around each bridge was evaluated, and appropriate airspace clearances were requested through an online application as required. This was particularly applicable to the Veterans Remembrance Bridge in Bangor, ME, since it is located within the Bangor International Airport Class "C" airspace. This location had automated clearance up to 150 ft above ground level, and thus requesting and receiving authorization to fly using the automated application process was very simple.

- *Platform endurance*. The flights were planned based on the average endurance of the batteries for each of the UAS. The planned length of each flight was discussed in terms of what was to be accomplished and the expected battery life available to ensure image collection was maximized.

- *Sensors*. Three EO sensors were used during the field tests. Two were mounted directly on the front of the UAS; one had a tilt range from −90 degrees to +30 degrees, and the other had a tilt range of −90 degrees to +90 degrees. Each was capable of 360 degrees of horizontal pan using the platform yaw control, allowing the pilot and inspector to obtain images in all directions. The third camera had a tilt range of +40 degrees to −130 degrees and a pan range of ±160 degrees.

- *Pilot and observer coordination*. During the flights, the pilot focused his attention on navigating the UAS into position to capture images and on making sensor adjustments, while the other members of the team acted as visual observers to ensure the UAS did not drift into the bridge structure or any other obstacle.

- *Control mode*. The UAS were operated using single-pilot control with no camera control available for the inspector. This mode of operation required the inspector to look over the shoulder of the pilot and direct the pilot to train the camera on specific areas of interest.

- *Qualifications of the inspection team*. The pilot used for these flights was a current, proficient, and certificated commercial UAS pilot. The bridge inspector was NBIS-qualified and had extensive experience.

- *Low light*. Lighting conditions under the bridges did not require external lighting to capture quality images. The team did employ external lighting, in the form of a modular light source that attached to the UAS and was operated via the UAS controller, for image comparison purposes. The external lighting did improve image quality in certain situations.

Sensor Settings and Specifications

ISO, shutter speed, and aperture (f-stop) are three camera settings that may be adjusted on the pilot console to control the quality of imagery.

- *ISO*. This setting adjusts the sensitivity of the sensor to light. Increasing this setting allows more light into the sensor, compensating for low-light conditions. Increasing the ISO setting can impact the quality of the image by making it appear grainy and reducing definition. For the images taken during the field tests, ISO was adjusted throughout the sensor's range to explore the limits of image usability for inspection purposes.

- *Shutter speed*. The shutter speed setting determines how fast the lens shutter opens and closes. Increasing this setting (more time open) allows more light into the sensor and can improve the sensor's ability to work in low-light conditions, but it can also cause blurring of the image due to movement or vibration of the UAS. The shutter speed was left in the automatic setting during the field tests.

- *F-Stop*. The f-stop is the setting that adjusts the diameter of the camera's aperture. The aperture is what determines the amount of light that is let into the camera's sensor. Because of the type of UAS sensors used, the f-stop was not manually adjusted for the flight tests.

The three sensors used in the field tests had the following specifications:

- Sensor 1:
    - Camera Resolution: 21 MP.
    - Sensor Type: 1⁄2.4-inch complementary metal-oxide semiconductor (CMOS).
    - Aperture: f/2.4 (fixed).
    - Zoom: 2.8× digital.
    - Shutter Speed: 1 to 1⁄10,000th s.
    - ISO Range: 100–3200 (video and image).
- Sensor 2:
    - Camera Resolution: 12 MP.

  - Sensor Type: 12.3-inch CMOS.
  - Aperture: f/2.8–f/3.8.
  - Zoom: Dynamic, with 2× optical and 3× digital.
  - Shutter Speed: 8 to 1⁄8,000th s.
  - ISO Range: 100–3200 (video and image).
- Sensor 3:
  - Camera Resolution: 20.8 MP
  - Sensor Type: 4⁄3-inch CMOS.
  - Aperture: f/1.7–f/16.
  - Zoom: Fixed.
  - Shutter Speed: 8 to 1⁄8,000th s.
  - ISO Range: 100–6400 (video); 100–25,600 (image).

INSPECTION 1: VETERANS REMEMBRANCE BRIDGE, BANGOR, ME (ROUTINE INSPECTION)

The Veterans Remembrance Bridge in Bangor is a highway bridge of girder construction built in 1986 that spans the Penobscot River (figure 34). The flights were conducted to simulate a portion of a routine inspection. In addition to the inspection and demonstration images, several images were collected to identify components that were in need of rehabilitation. Of particular interest during the inspection were the pier bearings on the east side of the bridge.

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Figure 34. Photo. Veterans Remembrance Bridge.

Traditional Inspection Results

During the previous MaineDOT routine inspection using traditional techniques, the inspection team determined that a bearing on pier 7 had shifted. The inspector at the time was able get measurements of the defect by accessing the area using the staging located on the east side of the pier. Figure 35 shows the inspector measuring the defect by hand, which required the use of a walkway located under the bridge to access the staging.

Figure 35. Photo. Inspector measuring bearing shift.

UAS Inspection Results

During the field test, the inspection team identified multiple defects during the course of the inspection with UAS. The team used the UAS to examine the same bearing shift defect for comparison purposes. Figure 36 shows the original UAS image that was captured, and the displacement of the bearing on pier 7 can be clearly seen. This image was collected with no interruption to traffic, and the team was located safely away from hazards.

The image of the bearing shift was then put through postprocessing to determine the distance that the bearing had moved off center. Figure 37 shows the postprocessed image with annotation of the applicable dimensions indicating the bearing is out of alignment by 6.78 inches. The offset was approximated based on a scaled image from known dimensions recorded when the ambient temperature was 70 °F.

While the pier 7 bearing shift is an example of how a UAS can be used to obtain images of defects without increased risk to personnel, the process would still require the inspector to compare the measurements to the theoretical position so that an engineering assessment could be made.

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Figure 36. Photo. UAS image showing bearing out of alignment.

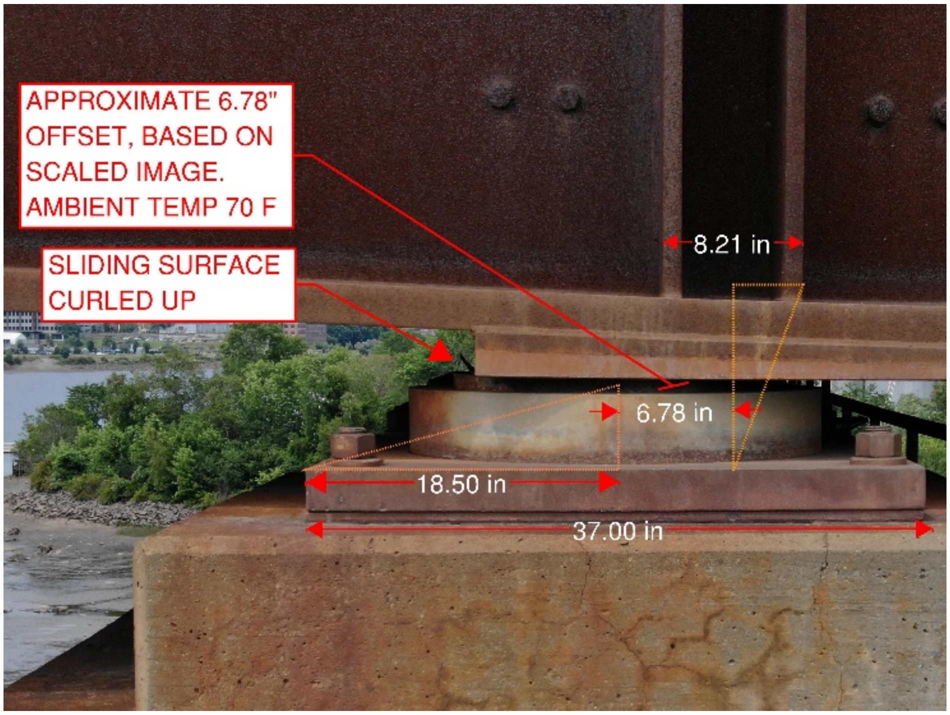

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Figure 37. Photo. Postprocessed image with dimensional overlay.

In addition to pier 7, the team identified other defects with the UAS. These defects were located in areas that, to get images with the perspective available from a UAS, would normally require lane closures and use of a UBIT to access. The following figures show several the defects identified and imaged from a UAS perspective. While not depicting defects that necessarily impact the structural condition of the bridge, the images show different angles, positions, and viewpoints of the bridge the inspection team was able to view as a result of employing a UAS.

Figure 38 is a downspout with significant decay.

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Figure 38. Photo. UAS image of defective downspout.

Figure 39 is an image snapshot from the 4K video captured by the UAS showing corrosion on a bridge sign structure.

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Figure 39. Photo. Snapshot from 4K video of overhead sign structure.

Figure 40 is an image taken by a UAS showing cracking on the foundation of pier 3 that would normally require boat access to inspect.

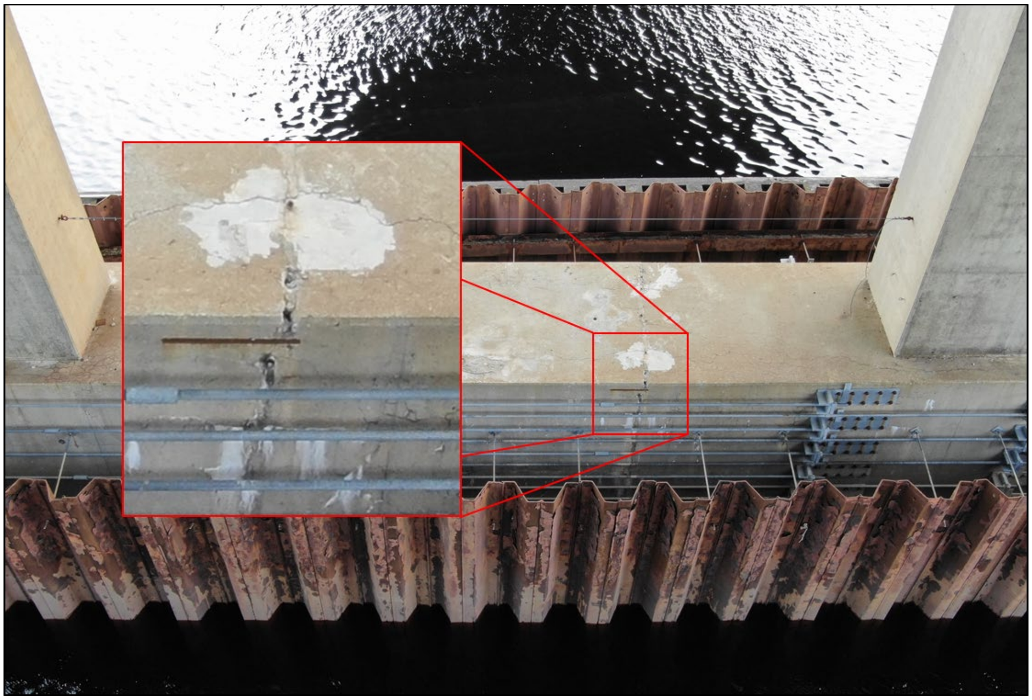

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Figure 40. Photo. Overhead image of preexisting crack on the foundation of pier 3.

Figure 41 is a snapshot from a 4K video showing joint, curb, and fascia degradation.

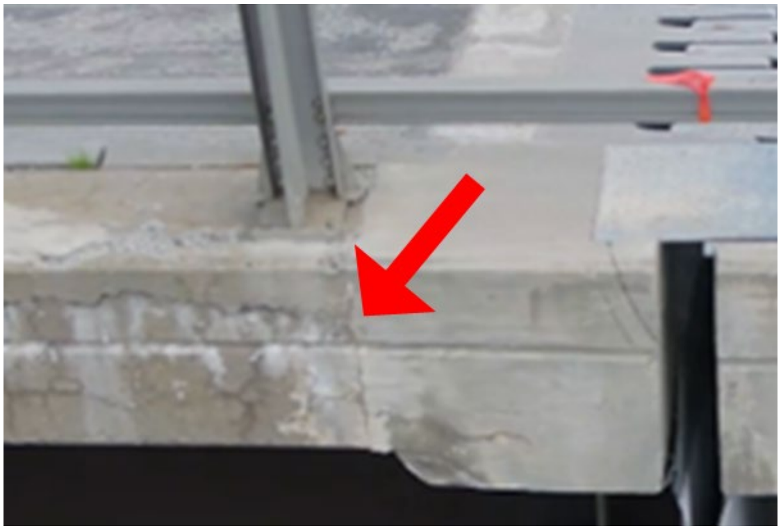

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Figure 41. Photo. Snapshot from 4K video showing the joint, curb, and cracking on the fascia.

Veterans Remembrance Bridge Observations and Findings

On this bridge, the major difference between the traditional inspection and the inspection conducted with the UAS was the ability to provide images of areas that would normally require lane closures and a UBIT. The UAS images of the bearing on pier 7 were sufficient to make initial measurements but would still need to be compared with the theoretical position.

The images in figure 38 through figure 41 show that a UAS can enhance the inspection process by reducing the need for traffic control and traditional access methods, thus minimizing risks to the inspection team, supporting personnel, and the traveling public. These images could not be obtained during a traditional routine inspection without special access equipment.

Another advantage of the UAS was the ability to capture 4K video, which could be reviewed postflight and postinspection to determine if a closer inspection was required of any bridge component, either while the team was still onsite or during a follow-up visit to the bridge.

The images of the bearing at pier 7 allowed the inspector to determine the distance the bearing had shifted, but did require postprocessing of the imagery offsite after the UAS inspection was completed. The image was scaled by taking the measurements from bridge plans and using them as a reference to determine the amount of displacement shown in the photo.

INSPECTION 2: SAGADAHOC BRIDGE, BATH, ME (ROUTINE INSPECTION)

The Sagadahoc Bridge is four-lane prestressed concrete segmental box girder bridge located on Route 1 between Bath and Woolwich, ME (figure 42). The bridge carries a high volume of daily traffic over the Kennebec River. The research team's inspection team leader had conducted a traditional routine inspection on this bridge earlier in the year.

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Figure 42. Photo. UAS image of the Sagadahoc Bridge.

Traditional Inspection Results

During the previous (traditional) routine inspection, the team employed a boat to observe and access key bridge components. While inspecting the bridge from the boat, the team noticed that the bearings at piers 8 and 9 were off center, as indicated by the red arrows in the image (figure 43). Due to difficulty in accessing the bearings, as well as concerns about safety, the team did not measure the bearing offset at that time.

The inspection team conducting the routine inspection had limited access to bearings on piers 8 and 9 from a built-in work platform. To fully access the bearings shown in figure 44 to obtain measurements, the inspector would have needed to either free climb to the top of the piers, exposing the inspector to increased risk, or use a UBIT, which would have required interrupting traffic flow.

Figure 43. Photo. Image of Sagadahoc Bridge piers 8 and 9 bearings captured by UAS.

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Figure 44. Photo. Image of bearing taken with handheld camera from the staging on the underside of the bridge.

UAS Inspection Results

Because the magnitude of the bearing shift was not measured during the routine inspection, the research team flew directly to pier 8 during the UAS test flights and worked with camera settings to achieve a usable image for approximating the bearing offset. Figure 45 is the raw image taken with the UAS.

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Figure 45. Photo. Raw image of the pier 8 bearing.

Figure 46 is the postprocessed image of the bearing. The postprocessing included magnifying the image, cropping and scaling the image, and adding overlays.

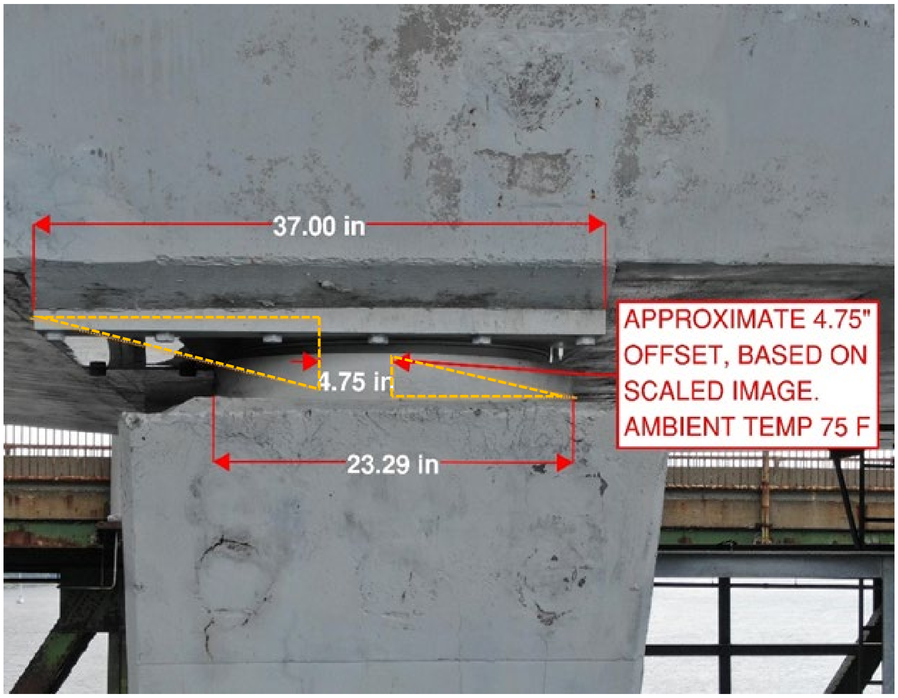

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Figure 46. Photo. Postprocessed image of pier 8 bearing with overlays.

The bearing offset was approximated at 4.75 inches based on the as-built plans (figure 47) and an ambient temperature of 75 °F.

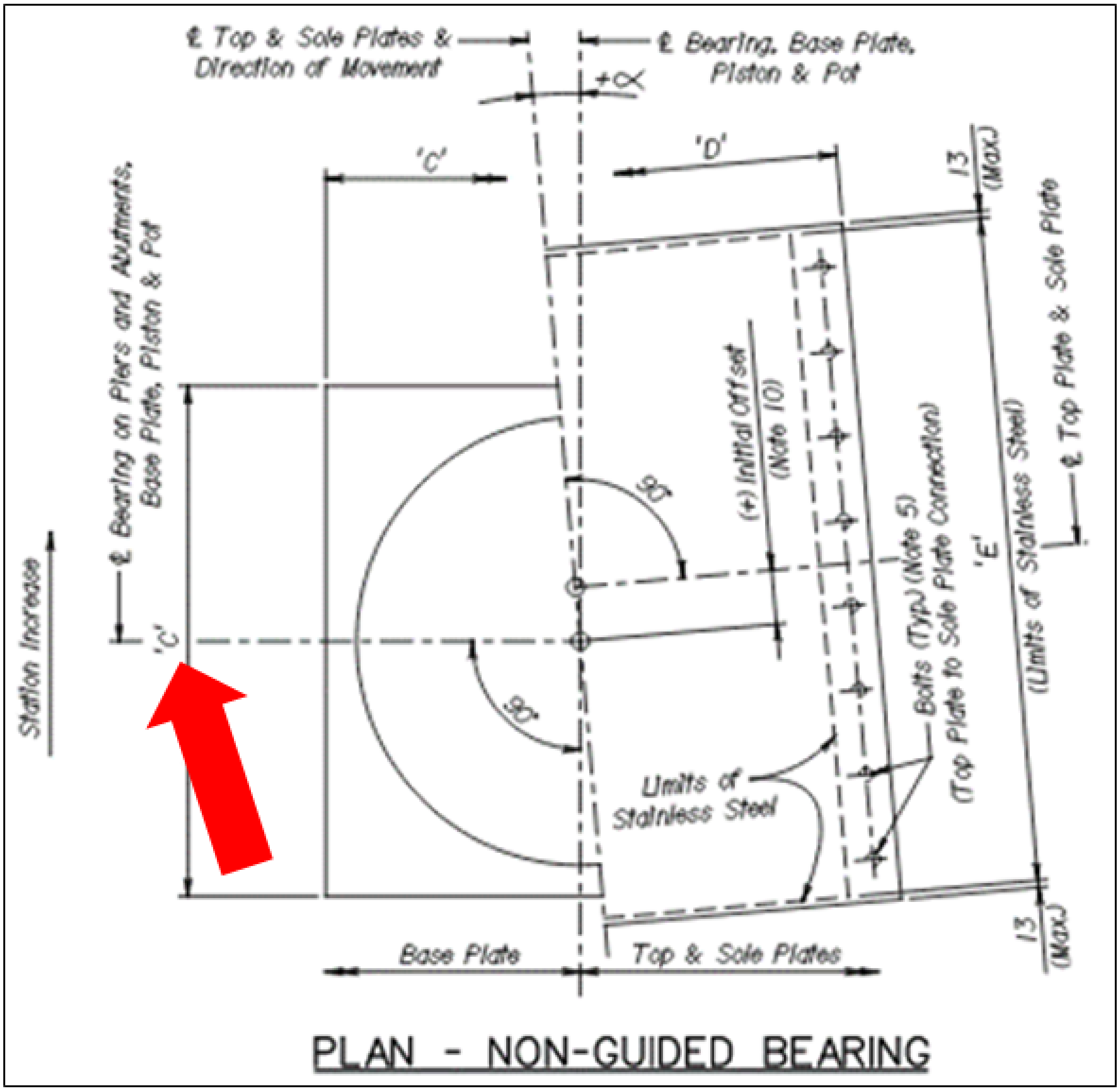

Figure 47. Illustration. As-built drawings of the pier 8 bearing.

The dimension for the top plate was taken from "C," indicated by the red arrow in figure 47, and was given as 37 inches.

UAS Logistics Challenges

Using the UAS allowed the inspector to obtain images of the bearings, which could then be put through postprocessing to obtain approximate measurements of the offset without increasing risk to the inspector or disrupting traffic. The primary challenge with using a UAS to inspect this bridge was accessing a site from which to fly. To reach an appropriate location, the team was required to the carry the gear over uneven terrain. One additional consideration was the proximity to the Bath Iron Works, which required a call to notify them that a UAS was operating in the area.

Sagadahoc Bridge Observations and Findings

In the case of the Sagadahoc Bridge, the UAS adequately captured images that could not otherwise be taken without risking inspector safety or creating an impact to the traveling public. Using the UAS removed the need for a boat, UBIT, and for inspectors to free climb to access the defect locations. The minor inconvenience of carrying the equipment outweighed the risk associated with traditional access methods.

Not included in this report was the requirement to access confined spaces in the segments. Confined spaces would be an area of the bridge that would benefit from a UAS with a protective cage and indoor stabilization; however, for these tests, confined-space flights were not attempted. At present, this type of UAS can be a costly investment of tens of thousands of dollars. Manufacturers are beginning to produce aftermarket cages for COTS UAS, however, and this will reduce the cost of using such a platform.

INSPECTION 3: MAX L. WILDER MEMORIAL BRIDGE, ARROWSIC, ME (FRACTURE CRITICAL)

The Max L. Wilder Memorial Bridge was built in 1950 and spans the Sasonoa River in Arrowsic (figure 48). The structure type is a steel-cantilever (arched), rivet-connected, polygonal-warren, through-truss bridge. The UAS test flights were flown prior to a scheduled fracture critical inspection to determine if a COTS UAS EO camera was sufficient to capture defects that would otherwise have to be located using standard industry practices for a fracture critical inspection. The focus of the inspection on this bridge was a previously installed repair to arrest developing cracks on several of the members.

Figure 48. Photo. UAS image of the Max L. Wilder Memorial Bridge.

Traditional Inspection Results

The inspection team leader for the UAS flights later joined the MaineDOT team to assist with the bridge's scheduled fracture critical inspection. The previous fracture critical inspections identified several fatigue cracks at the end of the floor beams that required preventative maintenance to halt the progression of the cracks. The area shown in figure 49 is an image of the fatigue crack location taken from a UBIT. This specific location was difficult to access and required the inspector to leave the bucket of the UBIT and to climb to further inspect the area located within the red circle in figure 49.

Figure 49. Photo. Defect location as seen from a UBIT.

Figure 50 shows the detail that was captured by an inspector that was within 18 inches of the defect with a handheld camera. One issue that the inspector had to account for when collecting this image was light infiltration into the space where the two components were connected. To prevent light infiltration, a piece of paper was placed on the outside of the connection point to block out the excess light.

Using traditional access methods, the inspector was able to clean the surrounding area to accurately determine the extent of the defect and the effectiveness of the previous repair.

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Figure 50. Photo. Photo captured by an inspector at 18 inches.

UAS Inspection Results

For the inspection with the UAS, a 12-MP camera was used. Figure 51 shows the image without any postprocessing, and it provides a rough approximation of what the image looked like on the UAS controller display.

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Figure 51. Photo. Defect location as seen from a UAS.

The image in figure 51 was taken from approximately 5 ft from the defect. A significant issue for collecting this image was the inability to maneuver the UAS into a position that was within arm's length or closer. The inability to maneuver within arm's length was the result of two factors: the complexity of the structure, which created an increased risk of the UAS making contact with the structure when in close proximity to the bridge components, and the instability of the UAS, even though it was equipped with indoor stabilization. The cause of the instability could not be determined, but some possible explanations are electromagnetic interference from the structure itself, the power lines adjacent to the structure, or a combination of both.

Another factor that inhibited the inspector's ability to collect a quality image using the UAS was light infiltration from the space where the two components were connected. This light infiltration created a significant amount of glare and reduced the quality of the image, making it difficult to fully capture the defect.

Max L. Wilder Memorial Bridge Observations and Findings

During the traditional inspection, accessing the defect required the inspector to exit the bucket of the UBIT, free climb to the location to clean the defect, and ultimately capture an image that adequately displayed the defect. While this approach is not uncommon, it increases risk to the inspector. Conversely, while the UAS was able to be flown from the relative safety of the ground, in this instance, the surrounding area could not be cleaned to determine the extent of the defect and the defect could not be adequately captured by the camera.

Figure 52 and figure 53 provide a comparison of the quality of the defect images captured during the two inspections. Figure 52 was obtained by the inspector within arm's length of the defect, while figure 53 is an image of the same defect that was captured with a UAS at approximately 5 ft. The image in figure 53 was enlarged approximately seven times to show a scale similar to that achieved by the inspector. As can be seen, the lighting is very poor, and the enlargement does not provide the detail needed to assess the defect.

When the UAS was employed to inspect this bridge, the intent was to determine whether it could provide suitable images to aid in the inspection of fracture critical members. As a result of several different factors, the inspector determined that, for this particular bridge, the UAS did not provide the quality of imagery needed to make an assessment of the defect, but that it was useful for assisting in locating areas that required a hands-on inspection.

One issue that reduced the efficacy of the UAS was the interference experienced with the indoor stabilization, which in turn impacted the ability of the pilot to maneuver the UAS closer than 5 ft from the defect. Another significant issue, relating directly to the overall usefulness of UAS for fracture critical inspection, was the lack of tools or instruments that could contact the surface of the bridge to clean, measure, and otherwise conduct a more detailed inspection of the defect.

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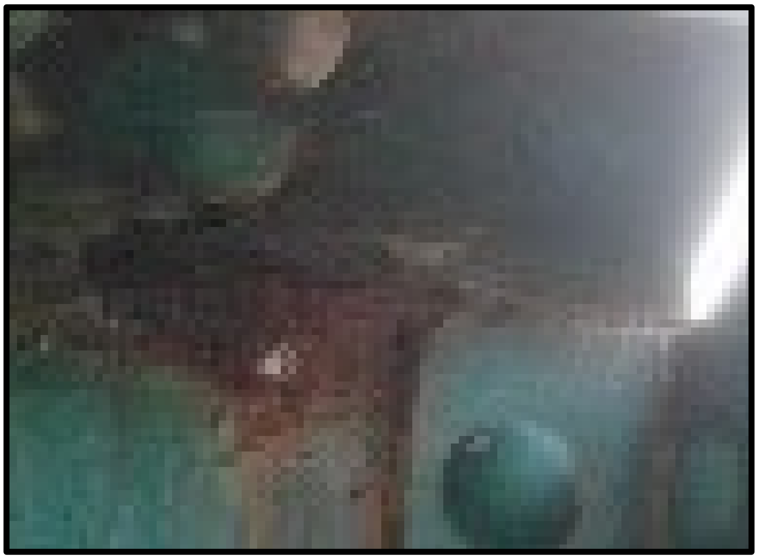
Figure 52. Photo. Inspector's photo.



© 2020 VHB.

Figure 53. Photo. Enlarged UAS photo.

INSPECTION 4: COOS CANYON BRIDGE, BYRON, ME (FRACTURE CRITICAL)

The final bridge flown was the Coos Canyon Bridge in Maine (figure 54). It is a single-span, steel through-girder and floor beam system with timber stringers, deck, and wearing surfaces and stone masonry abutments and wings. This bridge also requires fracture critical inspections. The surrounding terrain is very challenging for inspection teams; thus, examining the results using a UAS gave the research team an additional variable to explore.

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Figure 54. Photo. Coos Canyon Bridge.

In 2010 the bridge was load rated at 10 tons. In 2015 MaineDOT performed a hands-on fracture critical inspection of the bridge with a low weight UBIT. In 2016 the load rating was dropped to 5 tons, thus eliminating the use of a UBIT for future inspections. The bridge is currently scheduled for replacement.

The UAS research team performed a UAS inspection in August of 2019. Prior to the inspection, the team purposely did not review the most recent fracture critical report because the team hoped to scan the bridge for defects, if they existed, to test the defect-identification capabilities of the UAS. The traditional inspection results were examined following the UAS test flights.

Traditional Inspection Results

Because the previous inspection was conducted using a UBIT, the bridge was closed to traffic while the inspection was being conducted. Although not a high traffic area, use of the UBIT required detouring traffic to the nearest alternative crossing, approximately 1 mile away.

Using the UBIT, the inspector captured close-up images of defects. Because the inspector was close to the defects, precise measurements could be extracted from the images as well as the physical structure. In figure 55, a locking nut that had backed away from its original position can be seen, and the measurement of how far it had backed off can be obtained.

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Figure 55. Photo. Image of locking nut taken by inspector using handheld camera.

Figure 56 was also taken by the inspector with a handheld camera from the UBIT. The image clearly shows section loss on the hanger rod.

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Figure 56. Photo. Image of steel hanger rod taken by inspector using handheld camera.

UAS Inspection Results

The UAS team conducting the inspection was able to scan, identify, and collect images of the same defects that were noted in the previous fracture critical inspection as well as images that would have been difficult to capture using traditional access methods without closing the bridge to traffic. Using the UAS also enabled the team to locate their launch-and-observation site safely away from the road and pedestrian areas (figure 57). The inspection team did, however, decide to use safety observers (figure 57), due to high number of recreational users of the area during the time of year that the inspection was conducted, to prevent overflight of nonparticipating persons.

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Figure 57. Photo. UAS inspection team and safety observer.

The inspection included an overhead image (figure 58) of the bridge deck for establishing the overall condition. The length of the bridge was short enough the entire surface could be captured in one image.

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Figure 58. Photo. Overhead image of deck condition taken by a UAS.

Figure 59 shows the underside of the bridge taken from a UAS and looking straight up, as opposed to from an oblique angle. This perspective allowed the inspector to see cracking and end checking on the floor beams. To obtain similar images during a traditional inspection, the inspector would need to enter the water, which would be unsafe at this location.

Figure 59. Photo. Image taken looking straight up at the underside of the bridge deck.

As the pilot flew the along the bridge, the inspector was able to identify defects that had only been noted during previous inspections using a UBIT, demonstrating the usefulness of a UAS for inspections. Figure 60 shows a locking nut that has backed off or was not tightened at the hanger rod connection, as indicated by the red arrow, which is the same defect identified during the traditional inspection, as shown in figure 55.

Figure 60. Photo. UAS image of backed off nut on hanger rod.

Figure 61 shows an image of the same defect shown in figure 60, but it has been enlarged during postprocessing to allow the inspector to approximate the distance that the nut has backed off.

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Figure 61. Photo. Enlarged UAS image of backed off nut on hanger rod.

Figure 62 shows side-by-side images of the same section-loss defect. The image on the left was taken with no zoom, and the image on the right was taken at 2× zoom. The images are usable for noting that section loss is present, although the amount cannot be quantified.

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A. Nonzoomed photo showing section loss.

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B. Zoomed photo showing section loss.

Figure 62. Photo. Side-by-side comparison of images showing section loss.

Coos Canyon Bridge Observations and Findings

Overall, the UAS was able to collect the same images an inspector could while employing a UBIT. In addition, the UAS provided an added level of safety because there was no need for the inspector to use a UBIT, and traffic delay was eliminated because the bridge did not have to be closed.

The images captured by the inspector from the UBIT provided detail with which precise measurements could be taken or extracted from the image. The clarity of the images taken by the UAS were not sufficient to extract measurements, but were useful for making estimations, although some postprocessing was needed. The UAS was also able to capture imagery both above and below the deck. The imagery taken from above the deck captured the entire deck surface in one image, allowing a condition assessment to be made. At this particular location, it would not be possible for an inspector to take the images shot from underneath the bridge looking directly upward, without entering the river and placing themselves at risk in the moving water.

The imagery collected by the UAS during this test inspection could be used to generate an enhanced routine inspection or special inspection report. The enhanced routine inspection report gave the team leader the ability to view the bridge components at perspectives not attained using traditional inspection methods at this location. When comparing these images to previous inspection reports, including the fracture critical report from 2015, the inspection performed with UAS proved to have obtained images of the defects similar to those taken when using a UBIT.

FIELD TESTING FINDINGS

The results from the tests conducted in the field produced two main findings. First it was determined that UAS from each of the categories (i.e., consumer, professional, and commercial) were adequate to capture usable images, a fact that is widely accepted. Second, UAS cannot currently provide the same level of fidelity needed to conduct a fracture critical inspection. In addition to these two major conclusions, findings in the field focused around distance of the UAS from the structure, platform stabilization influences on UAS imagery quality, and the impact of lighting on sensor settings.

For the purposes of determining which settings produced results that could be used by the bridge inspection team leader to make decisions regarding the extent of a defect and condition of the bridge elements, the images were categorized as “usable” and “unusable.” However, due to the number of variables that must be accounted for, one image that can be used to determine the overall condition of an element may not in fact be usable in determining the extent of a defect.

Standoff Distance

The standoff distances determined to provide usable results without compromising the safety of the platform under a bridge were 6 to 8 ft horizontally and 3 to 4 ft vertically. When flying around the outside of the structure, the minimum safe distance had only a horizontal component, which was 6 to 8 ft. During the flight, these distances were estimated as the systems flown lacked the capability to measure true distances from the structure. The distance can be increased to provide an additional safety margin if the camera is equipped with either a digital or optical zoom capability. The images in figure 63 show what an object looks like when taken from varying distances.

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Figure 63. Photos. UAS images taken at varying distances from the bridge structure.

The images taken at 15 and 25 ft were immediately usable for evaluating the position of the bearing plate. The image taken at 60 ft was unusable while the UAS was flying but was usable once the image was placed on a computer display and enlarged.

The distances in these images were initially estimated in the field and then verified using KML shape files and a measuring tool (figure 64). The red dots represent the UAS position relative to the bridge at the time the image was captured.

© 2018 Google®. FHWA modifications include red dots and text overlays to identify standoff distance from the bridge structure.

Figure 64. Image. Standoff distance determination using shape files.

Lighting Requirements

A primary focus of the lighting evaluation was underneath the bridge, especially during low ambient-lighting or reflected-light conditions, such as on a cloudy day. While lighting is important for inspecting the underside of a bridge, not every UAS comes with and external lighting capability. When external lighting is lacking, manipulating the camera settings can aid in capturing usable imagery.

The major focus in the field tests was on ISO setting, since this is what controls the sensor's sensitivity to light. In most cases, a minor adjustment to the ISO was sufficient for the inspector to obtain usable imagery with which to evaluate the structure for defects while in flight.

Lighting intensity at the field-test locations was not measured due to the lack of a light meter that could deliver the information remotely. Instead, the images were evaluated by the inspector for usability, and settings were adjusted until the image was usable. The settings were then further adjusted until the image was no longer useable to determine the effect of changing the ISO on image quality (figure 65). In addition to the ISO setting, external lighting was employed to determine its effectiveness in obtaining a usable image.

Figure 65. Photo. Images of the underside of a bridge deck taken with different ISO settings.

Even though ISO was the primary focus in the field, due to the seemingly limited availability of external lighting on COTS UAS, one system that was employed was equipped with an external lighting source. The external lighting was employed to determine its effectiveness in a field setting. The use of external lighting resulted in an image that was sharper and allowed the inspector to see with greater clarity the surface details on the member being inspected (figure 66).

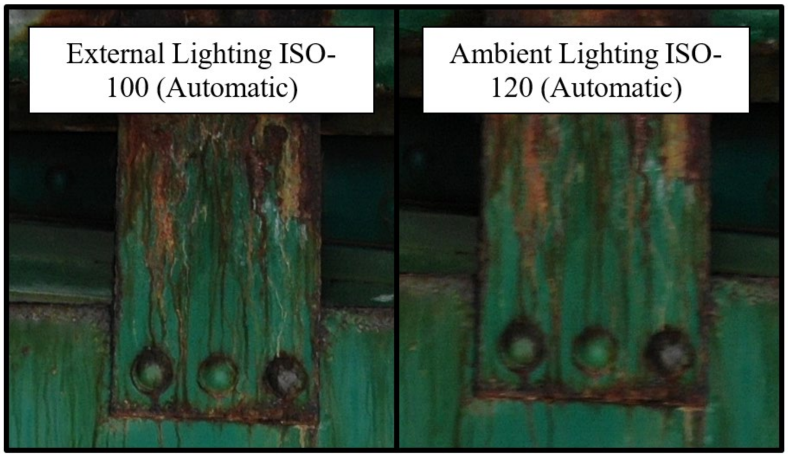


Figure 66. Comparison of images taken with and without external lighting.

In figure 66, the image on the left was taken with the UAS's external lighting on, and the image on the right was taken with no external lighting. In this case, the ISO was set to automatic. The camera adjusted the ISO to 100 with the external lighting on and to 120 with the external lighting off.

Field Evaluation of Platform Stabilization

UAS platform stabilization was monitored during the flights to determine its effect on image collection. Of the three platforms used, only one had a stabilization system that was effective in the absence of a consistent GPS signal. However, even that stabilization system did not guarantee that the platform remained in a fixed position. Stabilization was of particular concern while flying under the Max L. Wilder Bridge due to its structure. The platform experienced some drift, for which the pilot was required to compensate manually. This drift created issues with capturing images of areas that an inspector would normally be able to evaluate if accessing the bridge with traditional methods, such as a UBIT or by climbing.

GENERAL FIELD TESTING CONCLUSIONS AND RECOMMENDATIONS

During the field tests, several conclusions and recommendations were identified to aid in determining minimum specifications and operational considerations when using a UAS for bridge inspections. These recommendations were preliminary and were refined during part 2, the controlled-environment testing. The specifications and recommendations as determined in the field are as follows:

- Minimum Camera Specifications:
    - 12 MP.
    - Aperture: f/2.8 fixed.
    - Ability to adjust internal camera settings.
- ISO range 100–3200.

- UAS Specifications:
    - Recommended platform type is a multirotor to provide the ability to remain stationary while collecting images, as well as for greater stability
    - Optical stabilization is recommended for applications where GPS is degraded and when required to be within close proximity to the structure.
    - GPS is recommended to maximize stability and to ensure that images have accurate geotagging.
- UAS Controller:
    - The minimum control setup is one controller for the pilot with the ability for the inspector to view the video from the UAS to determine what images need to be captured. This method of control can be achieved by the inspector standing next to the pilot during flight and sharing the pilot's screen, or by slaving the video to a display for the inspector. The optimal setup for controlling the camera and the platform is to have two controllers: one for the pilot to control the platform, and one for the inspector to have independent control of the sensor and its settings.
    - The minimum screen resolution for the controller should be 720p to allow the inspector to either determine the extent of a defect in flight or capture an image and review it after the flight to make the determination.
- Camera Settings:
    - Due to the number of variables affecting the lighting of an image, determining a specific ISO setting is subjective to the time and place. Instances where the image quality is low due to the lack lighting can be improved by incrementally adjusting the ISO range until the image is clear enough to see the defect with the detail required to make an assessment. ISO was the only setting tested effectively in the field.
- Standoff Distance:
    - From the field tests, the recommended minimum standoff for the camera specifications listed is 6 to 8 ft. This distance will be dependent on the skill of the pilot at the controls. A skilled pilot can maneuver the platform much closer.
- Environment:
    - The environmental conditions during the field testing were generally benign. Maximum environmental conditions for operating the UAS around bridges should be based first on the manufacturer's recommendation.
    - It should be noted that even when winds are light, between 4 to 7 mph, rough conditions may be experienced when flying in and around the structure and adjustment to standoff should made accordingly.

PART 2: CONTROLLED-ENVIRONMENT TESTING

Controlled testing of the various UAS cameras and platforms was conducted at the University of Maine in Orono in a laboratory that included a wind generator and wave pool. The testing was conducted December 10–12, 2019. The research team composition was the same as in the field, with the addition of an observer from the FHWA and laboratory support personnel from the University of Maine.

The overall objective of the testing was to determine the minimum operating conditions in which a UAS can be effectively employed, and the minimum system specifications needed for those operating conditions.

Parameters for lighting, wind speed, and distance were tested. From these three categories, determinations were made regarding the minimum and maximum environmental conditions, minimum lighting conditions, minimum navigation and stabilization requirements, optimal sensor settings, minimum and maximum standoff distances, and maximum movement speed at which defects can be detected.

For this study, the defects used included a semicircular section of concrete, which contained cracking, along with high-quality images of defects taken at different bridges and printed to scale. One of the printed images depicted a steel bridge element. This image was captured during research performed at the Steel Bridge Research, Inspection, Training, and Engineering (S-BRITE) Center located at Purdue University, which studies bridge inspection processes and techniques.

The same UAS platform and sensor combinations used during the field testing were used in the laboratory setting.

MINIMUM VISUAL CAMERA SPECIFICATIONS

Each of the UAS sensor settings was independently adjustable, and each sensor was able to capture imagery using an automatic setting in which the sensor logic determines the setting combination that will produce the best imagery. When adjusting the settings manually, adjustment of one setting will typically require adjustment of another setting to maximize the potential to detect a defect. Minimum camera specifications for the various settings were determined by collecting a series of images at different distances, light intensities, and wind speeds. The defect models for this test consisted of half a concrete cylinder with a crack and images of different bridge elements.

Exposure

Images were captured under various lighting conditions to determine the camera's ability to compensate for lighting. The images below were taken 5 ft from the defect at approximately 1,100 lx to simulate the lighting intensity of an overcast day. Figure 67 is an example of a properly exposed image. The defect is a small crack inside the red bracket and is easily identifiable in the sample. The crack in the image measured 0.0008 inches at the narrowest end (on the left side of the red bracket) to 0.0018 inches at the widest end (on the right side of the red bracket).

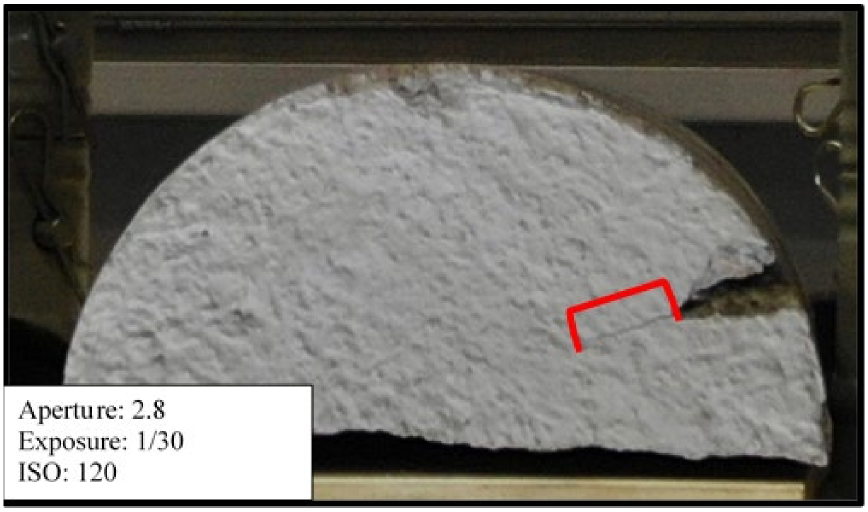


Figure 67. Photo. Properly exposed image.

Figure 68 is an example of an overexposed image. The crack in the image is inside the red bracket and cannot be seen in the image. The overexposure resulted in washing out the image to the point where it is unusable for assessing the defect.

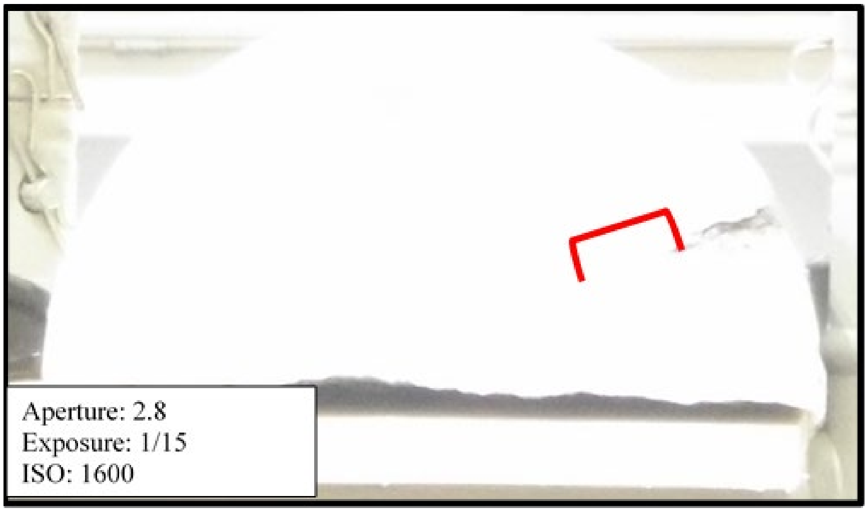
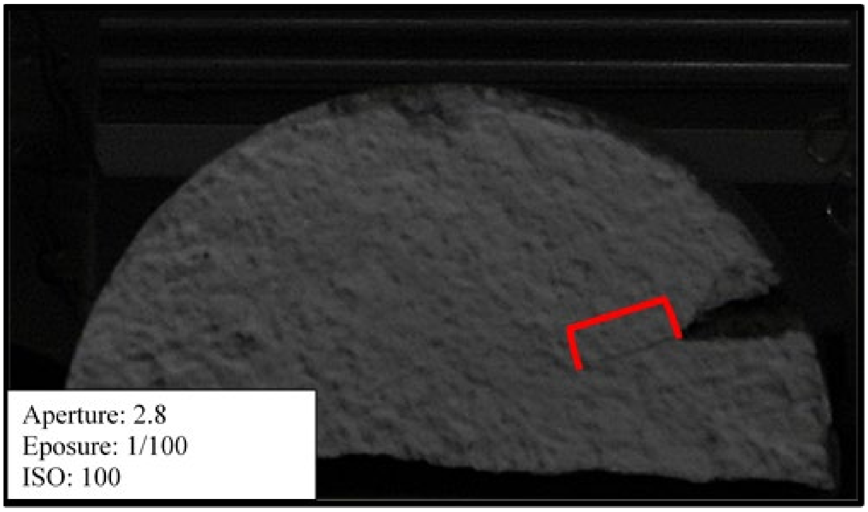


Figure 68. Photo. Overexposed image.

Figure 69 shows an underexposed image. The crack in the image is inside the red bracket and can be seen, but it lacks sharpness, making the crack less visible.



© 2020 VHB.

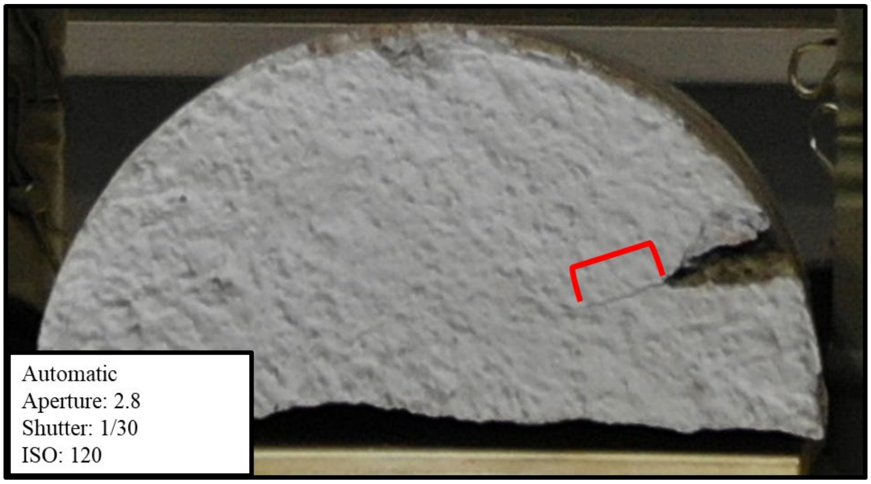
Figure 69. Photo. Underexposed image.

The exposure setting in these images was set manually, with the other settings determined by internal software to obtain the most usable image. Of the images presented, only one was determined to be immediately usable. Because of the technology in cameras available on the market, it was concluded that the best approach to obtaining proper exposure and high-quality, usable images was to allow the software to automatically calculate the proper settings. Not only does this result in better quality images, it allows the inspector to focus on inspecting the structure for defects and the pilot to focus on safely operating the platform.

Shutter Speed

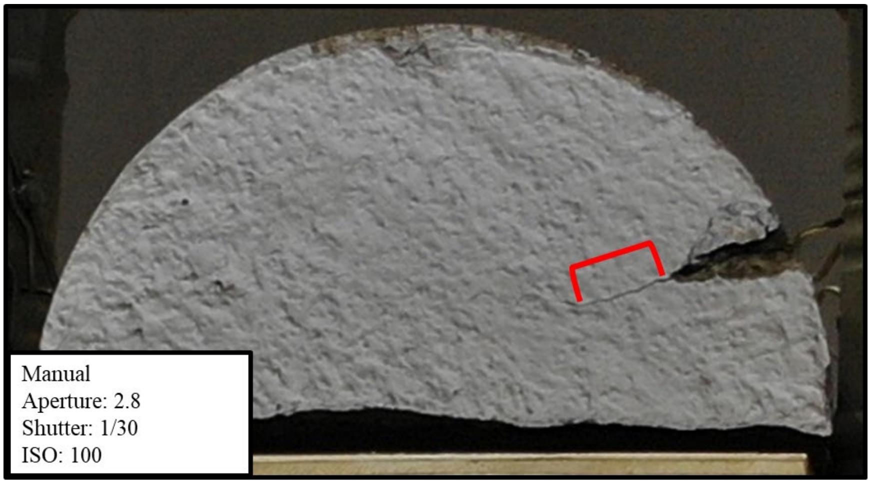
The shutter of the camera, when adjusted, determines the amount of time that the image is exposed to light. Shutter speed was tested to show how the images are impacted by changing the shutter speed in concert with the ISO. Each image was taken at 5 ft from the defect image or concrete specimen in lighting approximately equivalent to an overcast day at 1,100 lx. Shutter speeds of 1⁄15th, 1⁄30th, 1⁄50th, and 1⁄100th s were tested, with the ISO adjusted from 100 to 800 at each shutter speed.

Figure 70 was taken using automatic camera settings, and figure 71 is an image that resulted from changing the shutter speed manually. The manual settings were matched as closely as possible to the automatic settings.



© 2020 VHB.

Figure 70. Photo. Image of concrete defect taken with automatic settings.



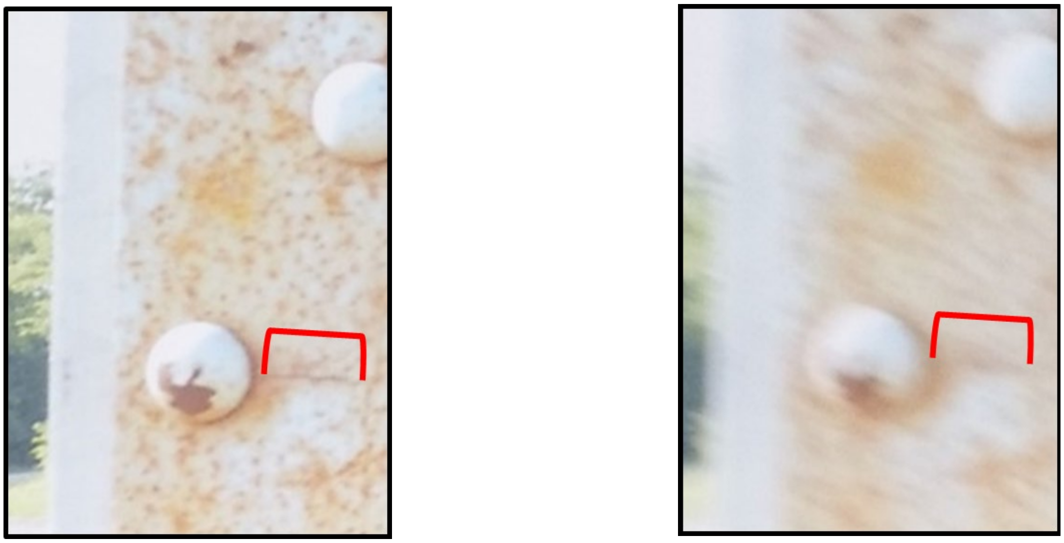
© 2020 VHB.

Figure 71. Photo. Image of concrete defect taken with manual settings.

When the two images are compared, the image taken with manual settings shows the crack with a greater resolution, although the crack is apparent in both images. These results may indicate that manual manipulation of settings may be needed when fine detail is required at a lighting level equivalent to an overcast day, although these findings do not indicate that this will be the case for every scenario that a bridge inspector may encounter.

Motion Blur

Motion blur is typically a result of movement of the camera and an improper shutter speed. A significant factor for capturing quality imagery with a UAS is stability. Instability in the platform will cause motion blur in the image. Instability can be a result of winds exceeding the UAS's operating limits or unstable GPS without a secondary stabilization system, as was the case in the images in figure 72, which shows side-by-side images of a riveted structural member. Figure 72-A is without motion blur, while figure 72-B is affected by motion blur.



Original photo: © 2020 Marc Maguire.
Sensor-captured photo of original: © 2020 VHB.

A. Motion blur example with exposure at 1⁄30th s and ISO set to 400.

Original photo: © 2020 Marc Maguire.
Sensor-captured photo of original: © 2020 VHB.

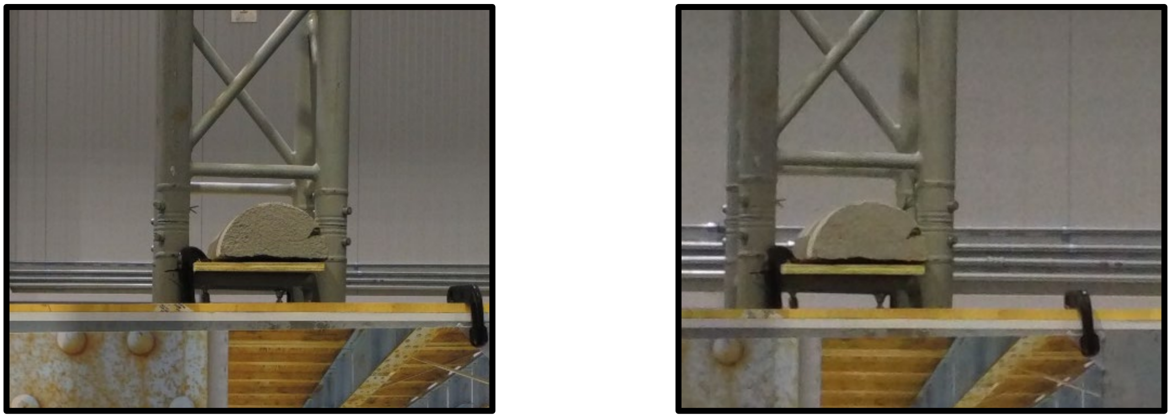
B. Motion blur example with exposure at 1⁄8th s and ISO set to 800.

Figure 72. Photo. Image comparison of motion blur.

The images were captured at approximately 10 ft from the defect and then cropped and magnified using basic postprocessing techniques to highlight the reduction in quality that motion blur causes. In figure 72-A the crack in the member can be easily identified, whereas the crack is virtually indistinguishable in figure 72-B. The images were taken using a UAS that had neither an adequate stabilization system nor active GPS due to the laboratory environment. A very fast shutter speed can minimize motion blur, and bright ambient lighting or augmented lighting, using an external source attached to the UAS, may provide the environmental conditions for sensor settings to eliminate motion blur when UAS stability is suspect.

Distance Versus Zoom

The effect of zoom was tested to determine variances in image quality when taken at different distances from the bridge element using the zoom function. The goal was to achieve an image quality that was roughly the equivalent of being within 1 ft of the structure. To determine these equivalent distances, images were captured at 5, 10 and 15 ft, both without zoom and with maximum zoom. Two of the three cameras that were used could magnify the image up to 2× or 3× magnification. The images in figure 73 were taken from 5 ft without zoom (figure 73-A) and 15 ft with 3× digital zoom (figure 73-B). The images taken at maximum zoom were taken using a digital zoom and therefore may have resulted in a loss of resolution when magnified.



A. Photo at 5 ft with 0× zoom.

B. Photo at 15 ft with 3× zoom.

Figure 73. Photo. Zoom comparison at 5 ft and 15 ft.

Even though the images presented in figure 73 cannot fully display the quality of the images as seen in person, it initially appeared that an image taken using 3× digital zoom at 15 ft provides nearly the same resolution as an image taken at 5 ft with no zoom. The difference in resolution, however, became clear during postprocessing. Figure 74 shows the same defect images enlarged four times from the original size.

A. Photo at 5 ft with 0× zoom.

B. Photo at 15 ft with 3× zoom.

Figure 74. Photo. Enlarged images showing loss of resolution.

The images in figure 74 highlight the loss of resolution that comes with using a digital zoom capability. As with all the images that are captured during an inspection, it will be up to the inspection team leader to make the determination regarding usability. In this instance, figure 74-B was not usable for assessing the defect but may be useful for identifying an area that needs further inspection.

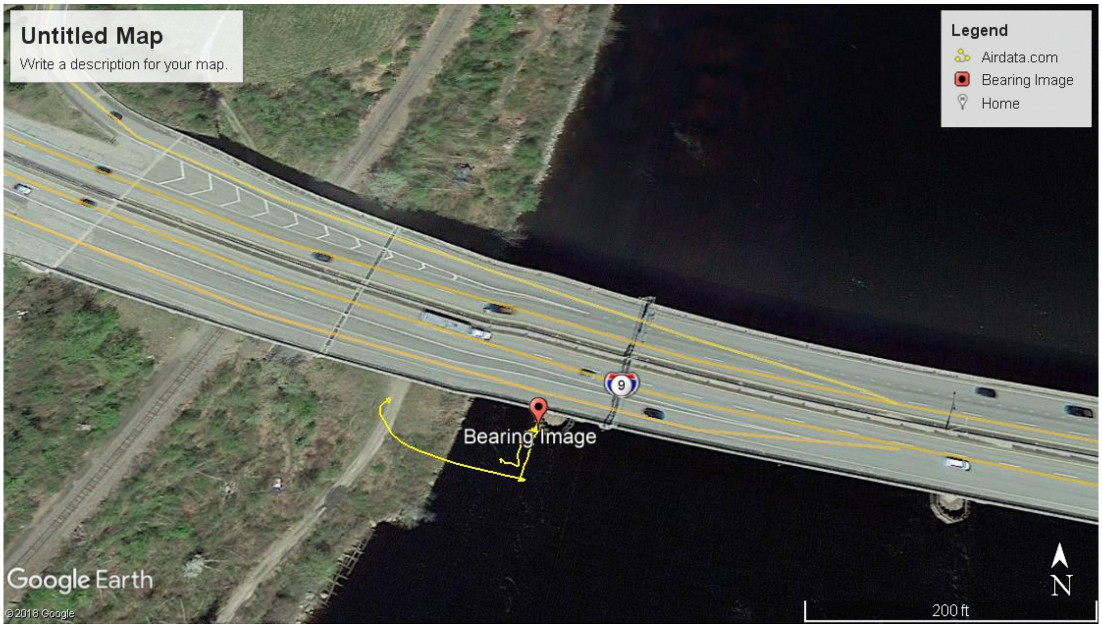
NAVIGATION AND LOCALIZATION

The ability of the UAS to remain stable and safely navigate around the bridge structure often relies on GPS. GPS provides accurate information on the location of the platform (e.g., latitude, longitude, altitude) as well as three-axis stabilization information for flight stability. If the GPS is unavailable, unless it has an alternate means to provide automatic stabilization inputs, the system will become unstable in flight and will lose the ability to provide location data (geotagging) for the images collected.

Localization

With GPS enabled and a solid GPS signal, the platform will remain very stable in flight even in a static position. The GPS can also provide UAS postflight flight-path data that can be uploaded to a mapping system that the user can then use to view the platform's location during each stage of the flight. The flight path data enables the user to effectively review the flight path and add markers to identify where each image was taken, and it allows future inspectors to repeat the same flight path using what is essentially a premade flight plan. The flight path will allow these inspectors to view defects located during previous inspections more easily.

A possible use for this technique may be marking defect locations on a fracture critical bridge to ensure that each is cataloged in a flight plan for subsequent inspections. Figure 75 is an example of a map showing a flight path that was recorded using GPS and marked with the location where images were taken.



© 2018 Google®. FHWA modified to add overlays showing aircraft position and flight paths.

Figure 75. Photo. Example of a map image with flight path and image location.

The yellow line in figure 75 is the UAS flight path overlaid on the map image, and the red marker with the black dot in the center is the location where the image was taken.

Stabilization

One of the riskiest uses of a UAS during a bridge inspection is inspecting under the structure. There are several reasons for this, the primary one being the lack of a solid GPS signal. A secondary reason is the bridge structure, which can create turbulence even in minor winds, and may cause the UAS to inadvertently shift its location without pilot input. During normal operations with a GPS signal, the UAS will maintain its position with a high degree of accuracy. However, when GPS is lost, as is likely to occur under the structure, platform stabilization is entirely dependent on the pilot’s skill. Loss of GPS requires the pilot to anticipate wind conditions and react in a timely manner to avoid contact with the structure.

To avoid relying solely on pilot input to maintain stabilization in the absence of GPS, many UAS are now equipped with stabilization systems that will keep the UAS in a stable relative position when signal reception is denied.

UAS stability in varying wind conditions was tested in the laboratory on two different systems with indoor stabilization to compare the inherent stabilization of those two systems against a system that does not have indoor stabilization. The UAS equipped with stabilization systems were able to sense the change in the platform location, automatically compensate in winds of 20 mph, and hold their positions with minimal lateral or horizontal movement. However, the number of corrections the systems had to make to hold its position created significant motion blurring and impacted the ability of the pilot to acquire usable images of the defects. Further testing in winds above 20 mph was not conducted for safety reasons.

The third system tested did not have indoor stabilization and was very unstable without GPS, requiring constant pilot input to maintain position with no external forces. When a wind of 5 mph was generated, the UAS became unstable to the point that the number of pilot corrections made the imagery collected virtually unusable for assessing defects. Testing was not attempted above the 5 mph with this platform for safety reasons.

Standoff Requirements

As described previously, standoff distance refers to the distance from the UAS to the bridge structure or defect. Based on the testing in the laboratory, in most cases 5 ft without zoom was sufficient to capture images of a defect. Capture of defect images was also accomplished in sustained winds of 15 mph with minimal effect on the images collected. However, this does not account for the potential of wind gusts in the field environment, and caution should be observed when attempting minimal standoff distances in the field.

The 5-ft standoff distance determined in the laboratory correlates well with the estimated standoff distances evaluated in the field test. If flight safety is a concern, and if the UAS in question has a zoom capability, this distance can be increased, as discussed previously, although there is a potential tradeoff in image resolution.

Of all the variables that could be accounted for in attempting to obtain minimal standoff, the pilot's skill is perhaps one of the most important and most subjective. The skill of the pilot should be the foremost factor in determining the standoff distance to be used during an inspection.

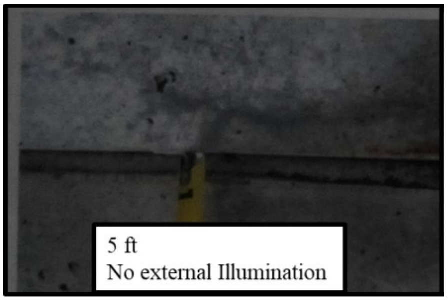
LIGHTING REQUIREMENTS

When using a UAS, having adequate lighting to capture quality imagery is a key parameter and can present challenges. The lighting conditions in the field can vary from very bright (as much as 100,000 lx or more on a sunny day) to near darkness (less than 50 lx under the under the bridge on an overcast day). As a reference, a typical room in a house is between 200 and 300 lx.

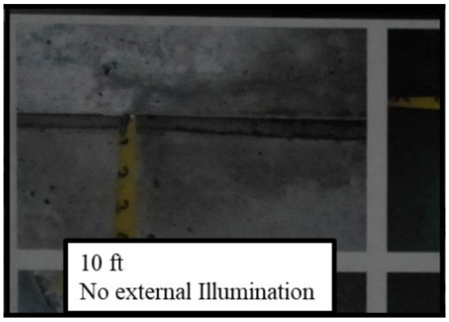
Because lighting conditions in the ranges that would be experience on a sunny day were unattainable in the laboratory, three different lighting conditions were used to simulate levels of light that could be experienced outside. They were medium or broken cloud layers (1,500–5,000 lx), overcast (1,500–100 lx), and dark (100–0 lx). To ensure consistency, all light measurements were taken at the center of the defect images with a light meter that measures from 0 lx to 100,000 lx. Testing was conducted using a UAS that had an external lighting attachment that provided 11 lx at 32.8 yd, 5,000 lx at 5 ft, and 50,000 lx at 3 ft.

External Lighting

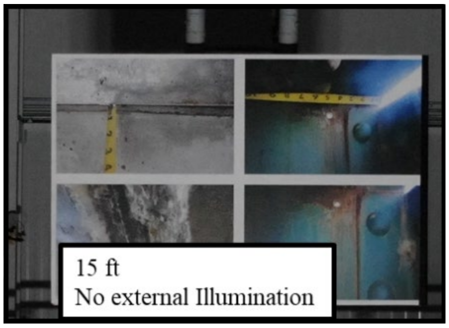
In some instances, the available light under a bridge is insufficient to adequately capture the images needed. Overcoming poor lighting conditions can be achieved by using external lighting if the UAS has the capability. The images in figure 76 were taken without external lighting at 5, 10, and 15 ft at a lighting intensity of approximately 50 lx.



A. Photo taken at 5 ft with no external illumination.



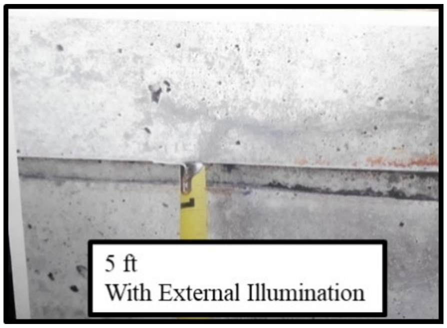
B. Photo taken at 10 ft with no external illumination.



C. Photo taken at 15 ft with no external illumination.

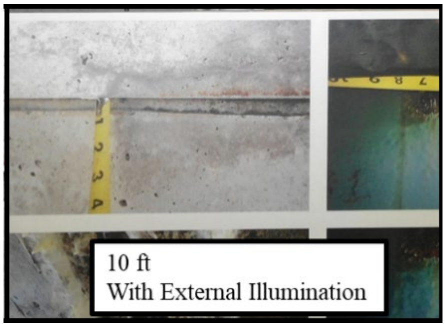
Figure 76. Photo. UAS test imagery with no augmented illumination.

The images in figure 77 were taken with external lighting enabled on the UAS. The image quality improved overall when the external light source was used, particularly at closer ranges. The test images suggest that external lighting beyond a range of 15 ft is of little value.



© 2020 VHB.

A. Photo taken at 5 ft with external illumination.



© 2020 VHB.

B. Photo taken at 10 ft with external illumination.

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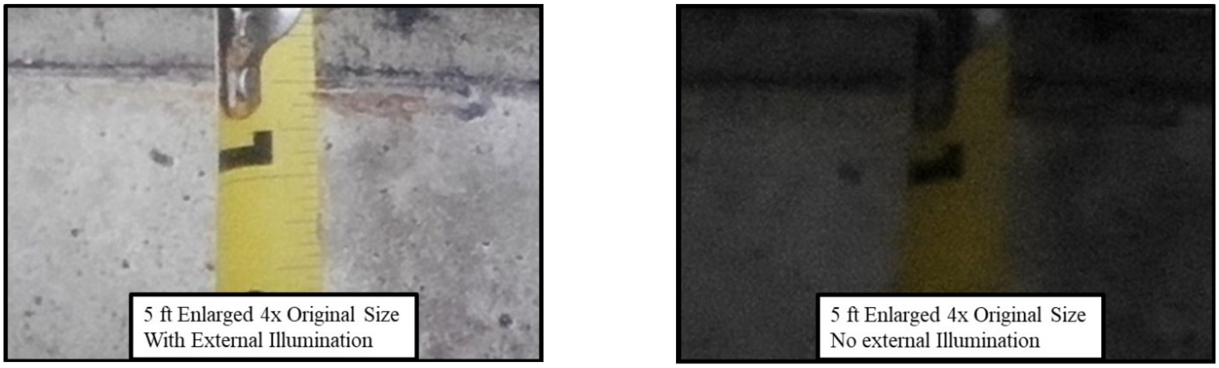
C. Photo taken at 15 ft with external illumination.

Figure 77. Photo. UAS test imagery using augmented lighting from the UAS.

The postprocessed images in figure 78 are enlarged to four times their original size and show the difference in image quality and detail between images captured with and without an external lighting source.

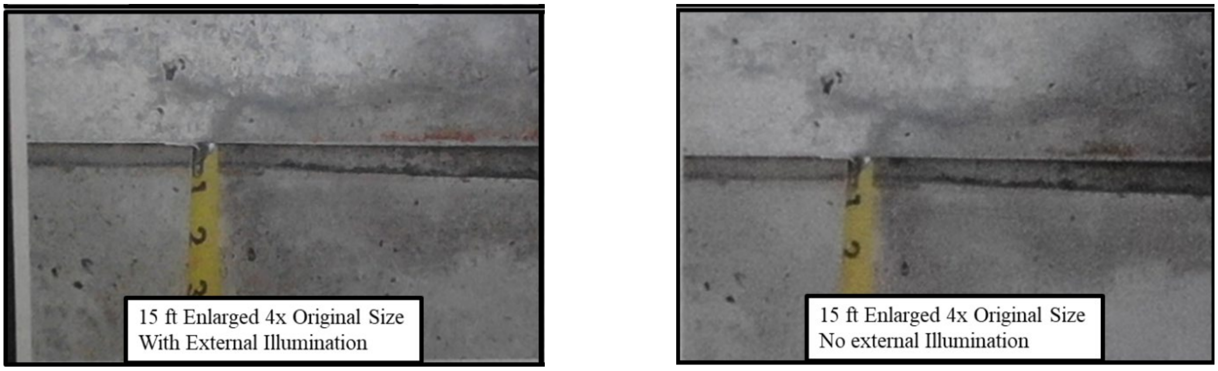


© 2020 VHB.

A. Photo from 5 ft, magnified 4×, with external illumination.

© 2020 VHB.

B. Photo from 5 ft, magnified 4×, with no external illumination.



© 2020 VHB.

C. Photo from 15 ft, magnified 4×, with external illumination.

© 2020 VHB.

D. Photo from 15 ft, magnified 4×, with no external illumination

Figure 78. Photo. Postprocessed image comparison.

Figure 78-A and figure 78-C were captured using external lighting. The biggest difference is the level of fine detail that can be achieved. The distance at which the external lighting improved the quality of the imagery was only tested out to 15 ft due to laboratory constraints.

It should be noted that, while external lighting was found to add value during field tests, the laboratory tests were conducted on high-resolution images of defects and therefore external lighting will likely have a different effect on actual bridge defects.

UAS SPEED FOR DEFECT DETECTION

The maximum velocity of the UAS that would allow image quality sufficient to detect defects was also considered as an additional parameter for testing. However, due to time constraints and lack of defect surfaces on which to conduct the test in the lab environment, the team decided to forgo this test.

As a rule, slower is better and stationary is best. Each inspection scenario will have different variables, and each must be taken into account. The optimum speed at which to detect defects will be best determined on site by the inspector based on their experience and subjective analysis of the imagery being provided by the UAS.

Other studies have been conducted that attempted to capture the best speed for detection, ODOT's research being an example. In that study, Gillins et al. (2018) concluded that the optimal speed for defect detection was less than 3.28 ft/s when the UAS was flown in a manner consistent with the perspective an inspector would have if they were using a UBIT or climbing. Higher rates of speed can be used when the UAS is flying farther away and high levels of detail are not required, such as in mapping.

SUMMARY

The concrete defect that was used for the laboratory tests had a crack that measured from 0.0008 inches at the narrowest to 0.0018 at the widest. The images used were of defects that were scaled to represent their actual size. The camera's ability to capture each defect was tested under various lighting conditions, wind speeds, and distances using three cameras and different camera setting. The resulting images were then reviewed to identify the defect and whether the images were usable for inspection purposes for that specific defect.

Overall, testing showed that the size of the defect is one of the most important factors in. determining the UAS standoff distance from which the defect can be photographed. Nearly as important is the quality of lighting. Bright and medium light conditions had little impact on image quality, but positioning the UAS between a defect and the prevailing light source will help ensure that the image is the highest quality possible. Lighting will affect the camera's internal automatic adjustments or require the camera settings to be manually adjusted, which can cause the image to become grainy in low-light environments. In this type of scenario, it was determined that allowing the camera settings to be automatically adjusted by the software typically produced the best results, reserving manual manipulation of the settings only when necessary, as determined by the inspector. The addition of external light on the UAS also proved to be useful in improving the quality of the images collected in low-light environments.

Wind had very little effect on the UAS that were equipped with indoor stabilization for wind speeds up to 15 mph, although the image quality can suffer in higher winds with gusting conditions.

Hundreds of images were captured during the laboratory testing, combining a wide variety of parameters. Appendix C contains a representative table, along with the associated images taken during the testing, to give the reader a sense of the amount of data examined.

RECOMMENDATIONS

The controlled environment testing revealed some findings that had not been verified during previous tests conducted in the field. It was not possible to test every possible combination of scenarios and variables, but among the significant findings from the testing described in this chapter was that, no matter the quality of the equipment, success in the field relies foremost on the inspection team leader and the UAS pilot (if different from the inspector). It is the pilot's experience that will direct the platform and sensor to the defect, and the inspector's expertise that will determine the severity of defect and whether further inspection is required.

The following are the recommendations of the research team from the controlled testing:

- *Use a minimum sensor resolution of 12 MP***.** The camera should have an inherent ability to produce quality images at 12 MP or higher. Nearly all UAS sensors available today have a resolution of at least 12 MP. Technology advances will only improve upon the minimum camera resolution available.

- *Use the sensor's automatic settings***.** The camera's ability to instantaneously and automatically calculate the appropriate settings will produce the highest quality results with the least amount pilot distraction. Settings on the camera are numerous, and to maximize results with manual manipulation of the settings would require training in photography. Using automatic settings is also the safest means by which to collect the images needed. Based on the settings tested and results of the tests, the camera should have the minimum ability to manually adjust the ISO from 100 to 3200, and the shutter speed setting, which controls exposure, should be manually adjustable from 1⁄15th to 1⁄100th s.

- *Adjust sensor settings manually when greater definition will add value***.** There may be a need to manually adjust the camera settings when automatic settings do not provide usable imagery. Typically, this will be unnecessary; however, it is an option to improve the image quality.

- *Avoid adjusting the shutter speed***.** Shutter speed is difficult to manage manually and should be avoided, especially at slow shutter speeds, as this can result in significant motion blur.

- *Adjusting ISO provides the best results*. Adjusting the ISO range outside of what has automatically been set by the software may result in a brighter image, but will add graininess, reducing the overall sharpness of the final product.

- *A standoff distance of 5 ft produces usable imagery*. The standoff distance from the bridge structure should be determined based on the comfort and skill level of the pilot. With a UAS that has indoor stabilization capabilities, a relatively safe distance is approximately 5 ft, but this can be extended if the system has an optical zoom capability.

- *Operate with wind conditions at 15 mph or less***.** Wind speeds over 15 mph generally degrade UAS flying qualities and the quality of the imagery such that the resulting images are unusable for inspection purposes. Inspection teams should gauge wind conditions, and the ability to fly and capture images effectively, at the inspection site. They should also consider how the UAS will be operated (i.e., with one control or a dual control setup). If one controller is used, and the inspector pilots the UAS while evaluating the defects, then the operating minimums should account for this since the inspector will be dividing their attention. Pilot experience is a key consideration in high winds. During these tests, a very skilled and experienced pilot was used to fly the UAS. He had difficulty in maintaining stability in turbulent winds at 15 mph and above. Winds above 15 mph also made it difficult to capture usable imagery due the attitude corrections that the pilot and the stabilization system had to make to keep the platform in its relative position.

- *Zoom can aid the inspector*. Zoom functions, although not required to capture adequate imagery, aid in extending the standoff and in providing a more detailed look at the structural elements, reducing the possibility of overlooking a defect.

- *External lighting will improve image quality*. Lighting has so many variables that each image must be evaluated in the moment to determine if the lighting is sufficient to create a quality image. In areas where lighting is limited, external lighting may produce enough light to capture the images needed if the platform is within 15 ft of the defect.

- *A stable, stationary platform produces the highest quality imagery*. In the absence of GPS, a UAS with indoor stabilization capability will aid in collecting images that can be used for assessing defects. Even though indoor stabilization is not required to operate in a GPS-denied environment, it will aid in reducing the potential for mishap, minimize motion blur, and decrease pilot workload.

CHAPTER 11. SUMMARY AND CONCLUSIONS

The speed of technological advances and the improvements discovered in the integration of new technologies is impacting industries and processes of all kinds. The inspection of bridges is no exception. More and more bridge stakeholders are using UAS, and they are exploring new ways to integrate UAS within established inspection guidelines.

Given the current state of UAS and sensor technology, along with existing FHWA and State inspections standards at the time of publication, UAS are best thought of as a means to get a camera into hard-to-reach areas to help detect and then capture images of structural defects. In short, a UAS is a flying, high-resolution camera. Bridge inspection program administrators, inspectors, engineers, and UAS operators are using UAS to augment traditional inspection techniques in many parts of the United States. They are exploring how UAS can replace or reduce the need for large and expensive access equipment, enhance safety by keeping inspectors on solid ground, downsize the need for traffic control measures, lessen traffic impacts and delays, and reduce lost travel time for commuters and the freight industry. UAS can reduce the cost of an inspection in some cases, but also presents data-management challenges. Advanced UAS platforms and sensors, along with skilled and experienced operators, may be necessary to achieve the maximum benefit.

At present, UAS are best used during routine inspections, particularly those for large, long, and complex bridges. On such bridges, the reduction in time required for an inspection using a UAS, compared with that needed for a traditional routine inspection process, may allow bridge owners to inspect more bridges in a shorter period of time, perhaps even allowing for more frequent special inspections of problem areas on key structures. Other key elements to ensuring that the UAS potential is maximized include training the pilot to operate in a GPS-denied environment, carefully planning each flight so the possibility of missing a defect is low, and maintaining the equipment according to manufacturer guidelines or by developing an internal maintenance plan. Maintaining open team communication during the entire inspection process, from planning through completion, is also critical to success.

The use of UAS for fracture critical member inspections is more problematic at present. Cameras and today’s sensors still have little capability to see through dirt, debris, and corrosion that can hide critical defects. The NBIS requires a hands-on inspection of fracture critical members; based on this research, most UAS are not currently able to satisfactorily replicate or serve as a substitute for this requirement.

Through this research, the FHWA is moving forward in partnership with bridge professionals in the field to identify efficiencies in inspection methods, reduce the cost of conducting inspections, and improve the safety of inspection teams and the public during the inspection process. Using UAS for bridge inspections is helping achieve these goals.

APPENDIX A. POLICY AND PROGRAM CONSIDERATIONS

This section provides a summary of information organizations may find beneficial when looking to establish a program to integrate UAS into their bridge inspection processes. The information contained in this appendix has been derived from several sources, specifically 14 CFR 107, FAA circulars and online resources, and the National Highway Cooperative Research Program of the Transportation Research Board.

ACCIDENT REPORTING

Any UAS accident or incident that meets the following criteria is required to be reported to the FAA within 10 d:

- Serious injury to any person or any loss of consciousness.
- Damage to any property, other than the UAS, unless one of the following conditions is satisfied:
    - The cost of repair (including materials and labor) does not exceed $500.
    - The fair market value of the property does not exceed $500 in the event of total loss.

UAS accidents are reported online by logging into the FAA DroneZone, or by calling the nearest FAA Flight Standards District Office. The DroneZone is found at https://faadronezone.faa.gov/#/ (FAA 2020a). FSDO locations and contact information can be found at https://www.faa.gov/ (FAA 2020b).

PRIVACY

It is important to note that the FAA does not regulate how operators collect data using UAS, meaning FAA does not directly address privacy in their rules. However, they do make a point of encouraging UAS users to become informed on the privacy rules and regulations in their respective areas. Because of the perceived potential for violation of privacy by the government, some States have prohibited the use of UAS by law enforcement without the issuance of a search warrant.

Privacy concerns should be a primary consideration anytime UAS operations are conducted on or near private property. Myriad laws cover privacy in general, and some State and local rulemaking bodies have adopted specific rules that apply to UAS operations. These laws impose various penalties for violations, and each organization operating UAS needs to identify what local, State, and Federal laws apply to their specific operations.

In addition to privacy laws, voluntary best practices can be employed to help build goodwill within communities where UAS operations take place. These practices include the following:

- Inform people who may be impacted by flight operations of the “5Ws:” the who, what, where, when, and why for the flight.
- Avoid taking and preserving images of private property and persons without consent.
- Avoid flying over private property without consent, if possible.

- Listen to and address people's reasonable privacy, security, and safety concerns.
- Know and comply with local, State, and Federal laws.

The complete guide to best practices is the *Voluntary Best Practices for UAS Privacy, Transparency, and Accountability*, produced by the National Telecommunications and Information Administration (NTIA) (NTIA 2016).

LIABILITY AND INSURANCE

Liability for UAS operators and organizations is a topic of significant interest within the UAS industry. Legal liability has been a source of hesitation for State DOTs in employing UAS as an agency resource for conducting bridge inspections, with some agencies opting to transfer liability by employing a contractor. While this may be the best option in some cases, it could restrain the DOT from realizing the full potential of UAS to contribute to the goals of the agency.

Before 14 CFR 107 was introduced, insurance companies would often cover UAS under their manned aircraft policies. Many different insurance companies now provide standard policies specifically for UAS, and some companies provide coverage on demand and by the hour.

STARTING A UAS PROGRAM

Starting a UAS program requires several necessary steps, which can seem daunting. This section discusses specific, basic items for consideration that have been identified as being relevant to a successful UAS program.

The information presented is the result of separate research on the use of UAS by transportation agencies. The research identified seven areas that are key to a successful program: executive support, organizational structure, policy and regulation, safety and risk management, training and crew qualifications, public relations, application, and operation. For more detailed information and a complete guide, see the report *Successful Approaches for the Use of Unmanned Aerial System by Surface Transportation Agencies* (National Cooperative Highway Research Program 2018).

Executive Support

Having executive buyin is one of the first elements needed to establish a successful UAS program. Starting small and beginning with an initial case study that highlights the benefits of employing UAS in cost, time, and safety across the various stakeholders can aid in gaining executive buyin.

Organizational Structure

Each organization will need to determine where the program will reside. Whether the program is added to an existing department or division or a new department is created, the program manager needs to have the expertise, or at least the organizational reach, to ensure the program is funded, maintained, and operated in accordance with State and Federal rules, regulations, and guidelines.

Policy and Regulation

UAS policy is rapidly changing to accommodate the dynamic nature of the industry. Program managers must keep up with these changes to ensure that organizational policies, along with State and local policies, are in line with Federal policies. With the number of policy factors in review or under revision, such as operating guidelines, waiver requirements, and certifications, it may be necessary to leverage resident expertise from within the agency to manage or assist in shaping organizational policy.

Safety and Risk Management

To maximize savings, increase operational efficiency, promote safe operations, and reduce risk, the UAS program should have policies and procedures that promote a positive culture of safety. Establishing a safety management system that documents and executes safety policy and assurance, manages risk, and promotes a safety culture will help ensure high levels of safety in UAS operations.

Training and Crew Qualifications

Establishing a comprehensive and progressive training program will develop professional aviators. The first step to building a training program is understanding the audience to be trained. If the UAS pilot is also a manned aircraft pilot, there will be distinct differences in the training developed versus the training needed for an engineer who has never operated any type of aircraft.

The training should be specific, highlighting the fundamentals throughout the entire training process. The goal is to produce a qualified and, if required, a commercial UAS pilot certificated under 14 CFR 107. The training program should address proficiency and currency as a metric for advancement through established qualification levels and the maintenance of flight skills.

In addition to flight operations training, there may be a need to establish training for various types of payloads and sensors used in the execution of inspections. Appendix B contains a sample syllabus that can be used as starting point to develop a standardized training program that ensures all pilots are trained to the same standard.

Public Relations

Engaging the public through an outreach program will ensure the public is informed about the purpose of the organization’s UAS program and the types of operations the public may witness. Such outreach provides an avenue to show the public that privacy laws will be followed and that UAS operations will provide a valuable public service by helping ensure public infrastructure is being maintained. It may also be necessary to develop an emergency response plan that can provide an immediate response from key personnel in the event of an incident.

Application and Operation

Developing a comprehensive plan for operational use is essential for developing and implementing a successful UAS program. The program will succeed if it starts small and expands based upon proven success. The organization should justify UAS use by highlighting increased safety, reduced liability, greater cost savings, and greater productivity. Additionally, leveraging the UAS across organizational disciplines, and sharing UAS assets throughout, can pave the way to acceptance and program success.

APPENDIX B. SAMPLE UAS PILOT TRAINING PLAN

This appendix provides an example of a training program established by a company that specializes in operating UAS for clients. The company that designed this training plan was a member of the research team and supports multiple bridge owners with UAS services for bridge inspections and other tasks using a variety of UAS platforms and sensors. This approach to training pilots augments the requirements established by the FAA for certificated commercial UAS pilots and serves to establish standards for UAS operator currency and proficiency.

UAS PILOT QUALIFICATIONS

Overview

This document provides an overview of the recommended commercial pilot training for general operation and certain specialized applications. The remote pilot levels have been broken down into three categories based on technical difficulty of the operation to be conducted. To qualify for each level, a pilot must complete mandatory ground and safety training, meet minimum flight hours, complete projects with an instructor, perform applicable flight maneuvers, demonstrate competency in emergency procedures, and be evaluated during live-flight operations. The pilot must prove competency in the type of data capture specific to the pilot qualification level. An instructor pilot will conduct a final evaluation under practical circumstances before approving the trainee for a pilot qualification level. The sections below list the goals, specifications, and training milestones a pilot must meet to achieve each of the three levels of pilot qualification.

Goals

- To establish a minimum standard and method of training UAS pilots to the required operating qualifications.
- To establish a foundation of continuous learning in the operation and safety awareness of operating UAVs and affiliated equipment.
- To establish a culture of safety throughout the company with an emphasis on management of risk factors associated with UAV operations and workplace safety.

Specifications

- Operations on a construction site, landfill, railroad, or powerline requires OSHA 10 certification and CPR/first aid training.
- Operations on rail right-of-way requires railway safety training.
- Operations on a powerline right-of-way requires training specific to operating in the wire environment, off-road vehicle operation and safety, and downed wire safety.
- Operations inspecting communication towers requires radio frequency safety training.
- Operations at night require ground training and night time flight training.

For each pilot level, a minimum number of hours must be flown per month to meet currency requirements. Minimum hours differ based on pilot certification level. Each pilot will be evaluated on a yearly basis by an instructor pilot. The evaluation period will further advance the pilot's skills, technical knowledge, and safety awareness.

Pilot Training Milestones

Level 1 Pilot

Applications: Oblique images, video

Min. flight hours: 10

Min. projects with instructor: 3

Hours/month for currency: 2

Sign-off qualifications:

General
- Demonstrate working knowledge of platform and ground station.
- Demonstrate airspace knowledge.
- Demonstrate knowledge of FAA regulations under 14 CFR 107.
- Pass the FAA Remote UAV exam per 14 CFR 107.
- Demonstrate company safety procedures.
- Earn certification in first aid and CPR.
- Demonstrate knowledge of air-traffic control communications.

Flight maneuvers
- Takeoff/landing without aid of GPS.
- Hovering without aid of GPS.
- Flying boxes without aid of GPS.
- Situational awareness.
- FPV operations for navigation.
- Emergency and lost link procedures.

Data acquisition
- Demonstrate mastery of camera settings for photos and video.

Level 2 Pilot

Applications: Photogrammetry and thermal mapping

Min. flight hours: 15

Min. projects with instructor: 3

Hours/month for currency: 3

Sign-off qualifications:

General

  - Demonstrate working knowledge of platform and ground station.
  - Demonstrate airspace knowledge.
  - Demonstrate knowledge of FAA regulations under 14 CFR 107.
  - Continually adhere to company safety procedures.

Flight Maneuvers

  - Operating knowledge of at least 2 mapping software programs.
  - Figure eights with forward facing movement.

Data Acquisition

  - Submit dataset with proper overlap and exposure.
  - Demonstrate mastery of camera settings for photos and video.

Level 3 Pilot

To achieve level 3 certification, a pilot must meet certain application-specific training requirements. The training varies depending on the skills required and hazards encountered for each type of operation. These operations include but are not limited to:

- Full bridge inspection (GPS-denied environment).
- Electric utility line inspection.
- Electric utility substation inspection.
- Communication tower inspection.
- Wind turbine inspection.
- Hydroelectric generation (dam) inspection.
- Industrial chimney/cooling tower inspection.
- Interior inspection (GPS-denied environment).
- Solar array inspection.
- LiDAR mapping.

Applications: Proximity flying and LiDAR

Min. flight hours: 20

Min. projects with instructor: 3

Hours/month for currency: 4

Sign-off qualifications:

General

  - Demonstrate working knowledge of platform and ground station.
  - Demonstrate airspace knowledge.
  - Demonstrate knowledge of FAA regulations under 14 CFR 107.
  - Continually adhere to company safety procedures.
  - Demonstrate knowledge of application-specific data acquisition.

Flight Maneuvers

- Figure eights with forward facing movement.
- Takeoff and landing with forward facing movement.
- Proximity flying without GPS assistance.
- Simulated application-specific data acquisition (e.g., mock bridge inspection).

Data Acquisition

- Demonstrate mastery of specific sensors and data acquisition methods for particular applications.
- Demonstrate appropriate data management procedures.

APPENDIX C. SAMPLE IMAGE-TESTING METRIC TABLE AND IMAGES

Table 8 contains a representative sample of the results of the various UAS sensor tests that were conducted in the laboratory at the University of Maine. It includes samples from each camera used. The images numbered 1 through 27 in the table correspond to figure 79 through figure 105. The reader should note that the images in this document may not accurately represent the detail or lack thereof for each simulated defect used. Additionally, the parameters listed for each image were calculated automatically by the camera's internal software and are presented as a reference for these particular tests. The images should not be considered as a baseline for collecting images as each scenario an inspector finds themselves in will have its own variables.

Table 8. Controlled environment sensor testing parameters (sample list).

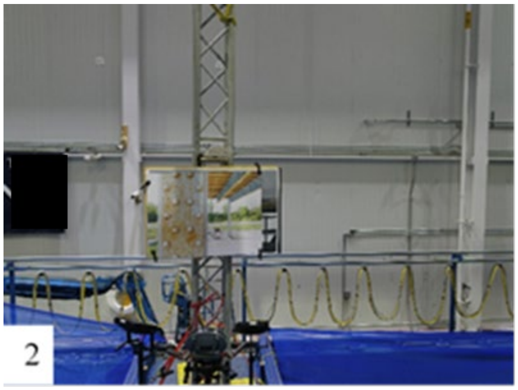
Image #	Defect Type	Wind (mph)	Distance (ft)	Lighting (lx)	Aperture	Exposure (s)	ISO	Zoom (Times)	Usable for Inspection
1	FC & Concrete	0	5	240	1.7	1/40	100	0	No
2	FC & Concrete	0	10	240	2.8	1/30	200	0	Yes
3	FC & Concrete	0	15	240	2.8	1/30	200	0	No
4	FC & Concrete	0	5	1500	1.7	1/120	100	0	Yes
5	FC & Concrete	0	10	1500	3.2	1/30	120	0	FC Only
6	FC & Concrete	0	15	1500	6.3	1/20	400	0	No
7	FC & Concrete	0	5	1600	2.8	1/240	100	0	Yes
8	FC & Concrete	0	10	1600	6.3	1/30	200	0	No
9	FC & Concrete	0	15	1600	2.8	1/40	100	0	No
10	Defect Image	0	5	10600	2.8	1/120	100	0	Yes
11	Image	0	5	10600	2.8	1/80	100	2	Yes
12	Image	0	10	10600	2.8	1/80	100	0	Top right unusable
13	Image	0	10	10600	2.8	1/60	100	2	Yes
14	Image	0	15	10600	2.8	1/100	100	0	Top right unusable
15	Image	0	15	10600	2.8	1/100	100	2	Yes
16	FC & Concrete	5	5	140	2.4	1/30	253	0	Yes
17	FC & Concrete	5	5	140	2.4	1/30	253	3	Yes
18	FC & Concrete	5	10	140	2.4	1/30	253	0	No

Image #	Defect Type	Wind (mph)	Distance (ft)	Lighting (lx)	Aperture	Exposure (s)	ISO	Zoom (Times)	Usable for Inspection
19	FC & concrete	5	10	140	2.4	1/30	253	3	Concrete only
20	FC & concrete	5	15	140	2.4	1/30	253	0	No
21	FC & concrete	5	15	140	2.4	1/30	253	3	No
22	FC & concrete	10	5	140	2.4	1/30	253	0	Yes
23	FC & concrete	10	5	140	2.4	1/30	253	3	Yes
24	FC & concrete	10	10	140	2.4	1/30	253	0	No
25	FC & concrete	10	10	140	2.4	1/30	253	3	Concrete only
26	FC & concrete	10	15	140	2.4	1/30	253	0	No
27	FC & concrete	10	15	140	2.4	1/30	253	3	No

FC = fracture critical.

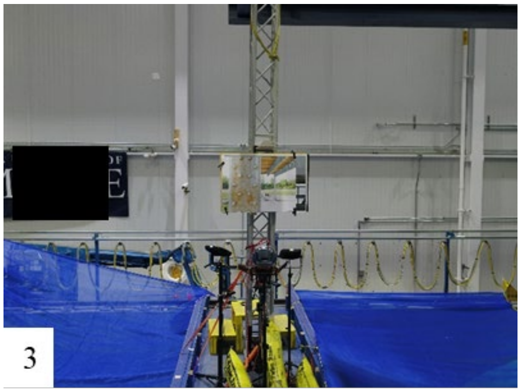
Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 79. Photo. Image 1, fracture critical member and cracked concrete sample taken at 5 ft.



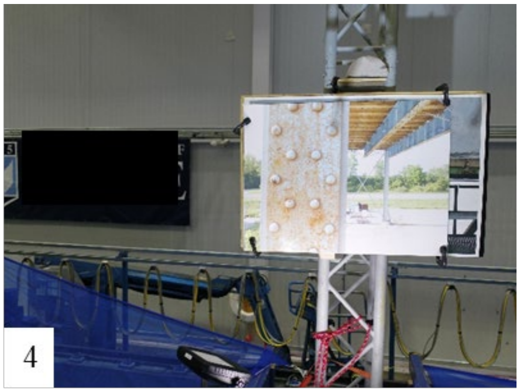
Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 80. Photo. Image 2, fracture critical member and cracked concrete sample taken at 10 ft.



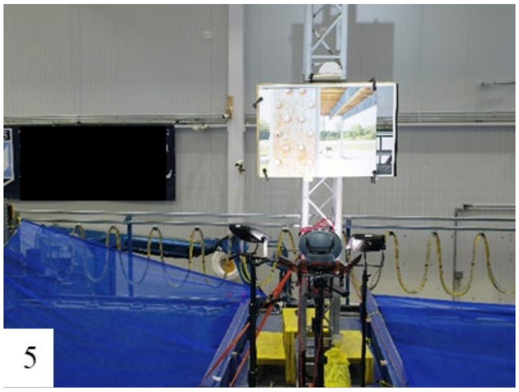
Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 81. Photo. Image 3, fracture critical member and cracked concrete sample taken at 15 ft.



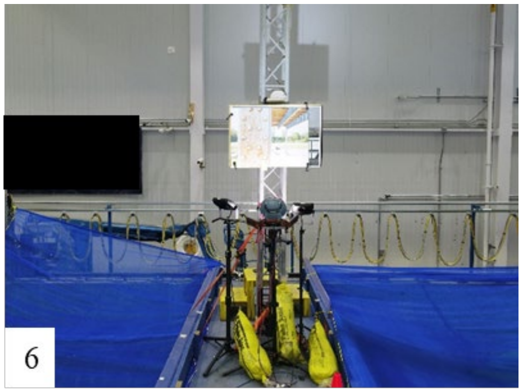
Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 82. Photo. Image 4, fracture critical member and cracked concrete sample taken at 5 ft.



Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 83. Photo. Image 5, fracture critical member and cracked concrete sample taken at 10 ft.

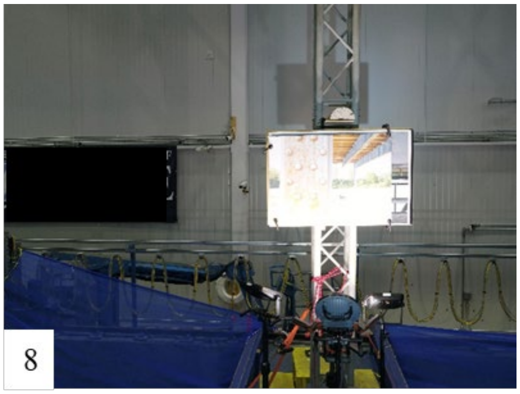


Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 84. Photo. Image 6, fracture critical member and cracked concrete sample taken at 15 ft.

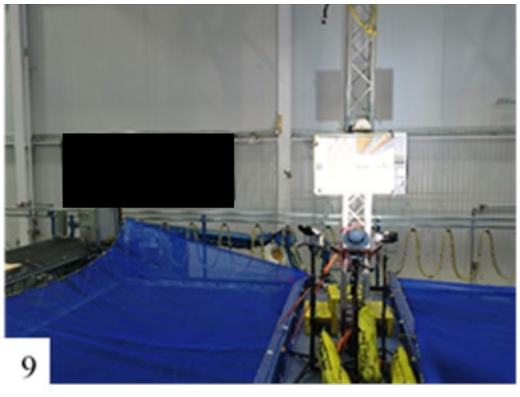
Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 85. Photo. Image 7, fracture critical member and cracked concrete sample taken at 5 ft.



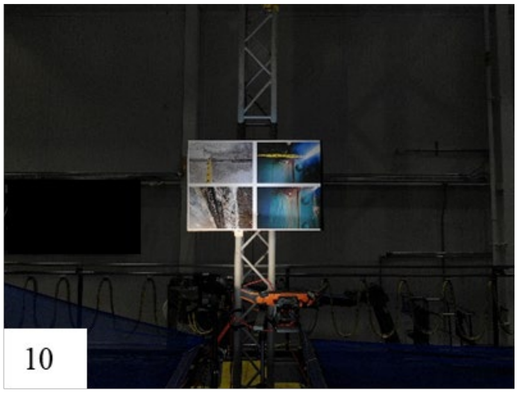
Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 86. Photo. Image 8, fracture critical member and cracked concrete sample taken at 10 ft.



Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 87. Photo. Image 9, fracture critical member and cracked concrete sample taken at 15 ft.



© 2020 VHB.

Figure 88. Photo. Image 10, composite of various defects taken at 5 ft.

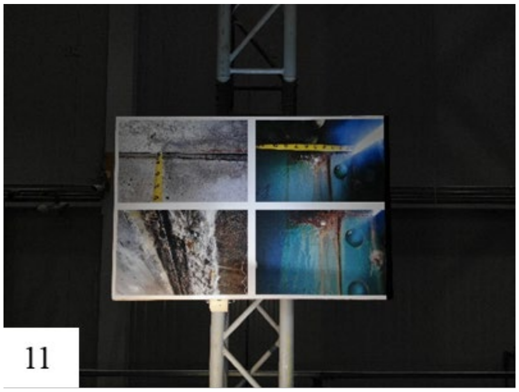
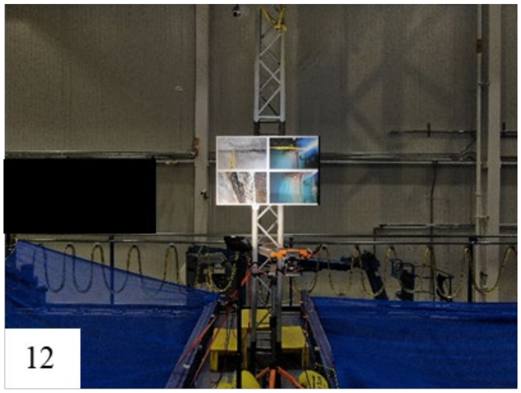


Figure 89. Photo. Image 11, composite of various defects taken at 5 ft.



[redacted]

Figure 90. Photo. Image 12, composite of various defects taken at 10 ft.

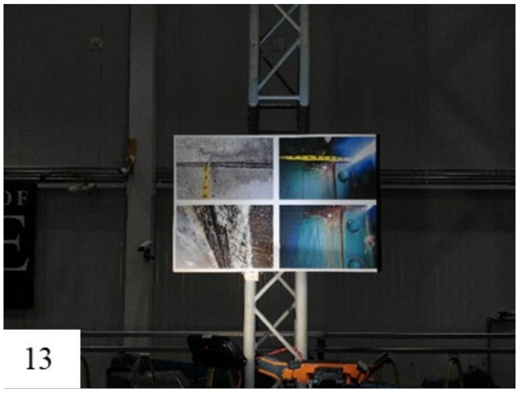


Figure 91. Photo. Image 13, composite of various defects taken at 10 ft.

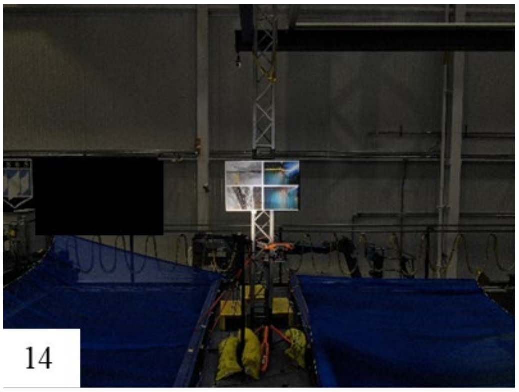


Figure 92. Photo. Image 14, composite of various defects taken at 15 ft.

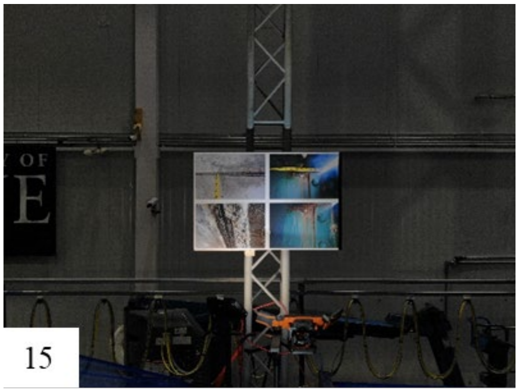
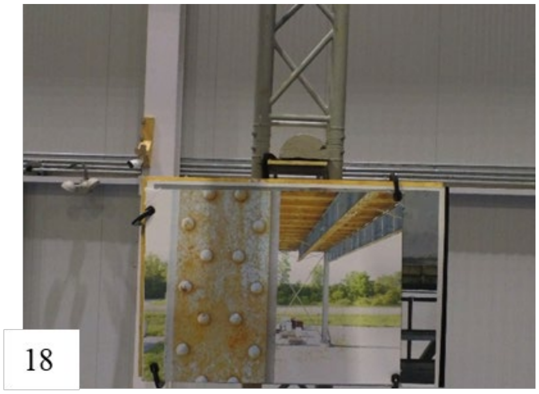


Figure 93. Photo. Image 15, composite of various defects taken at 15 ft.

Figure 94. Photo. Image 16, fracture critical member and cracked concrete sample taken at 5 ft.

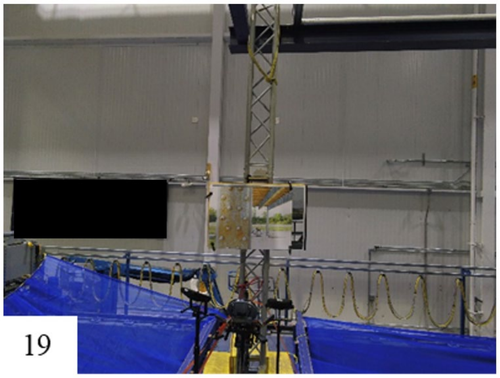
Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 95. Photo. Image 17, fracture critical member and cracked concrete sample taken at 5 ft.



Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

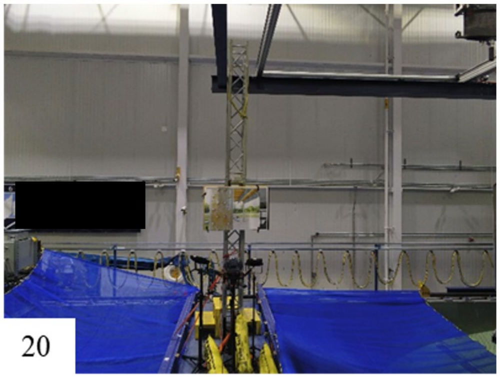
Figure 96. Photo. Image 18, fracture critical member and cracked concrete sample taken at 10 ft.



[redacted]

Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 97. Photo. Image 19, fracture critical member and cracked concrete sample taken at 10 ft.



Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 98. Photo. Image 20, fracture critical member and cracked concrete sample taken at 15 ft.

Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 99. Photo. Image 21, fracture critical member and cracked concrete sample taken at 15 ft.

Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 100. Photo. Image 22, fracture critical member and cracked concrete sample taken at 5 ft.

Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

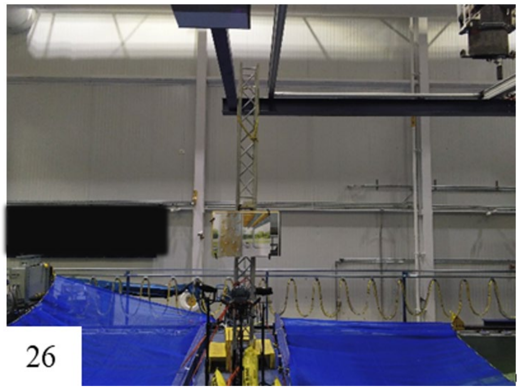
Figure 101. Photo. Image 23, fracture critical member and cracked concrete sample taken at 5 ft.

Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 102. Photo. Image 24, fracture critical member and cracked concrete sample taken at 10 ft.

Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

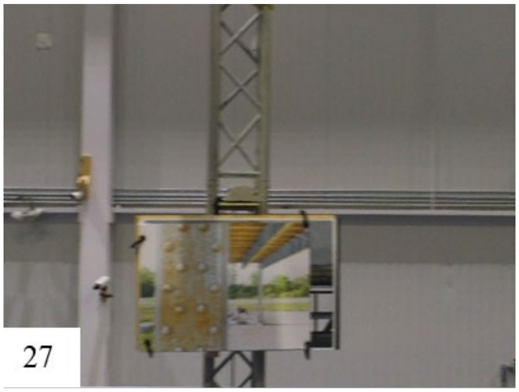
Figure 103. Photo. Image 25, fracture critical member and cracked concrete sample taken at 10 ft.



[redacted]

Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 104. Photo. Image 26, fracture critical member and cracked concrete sample taken at 15 ft.

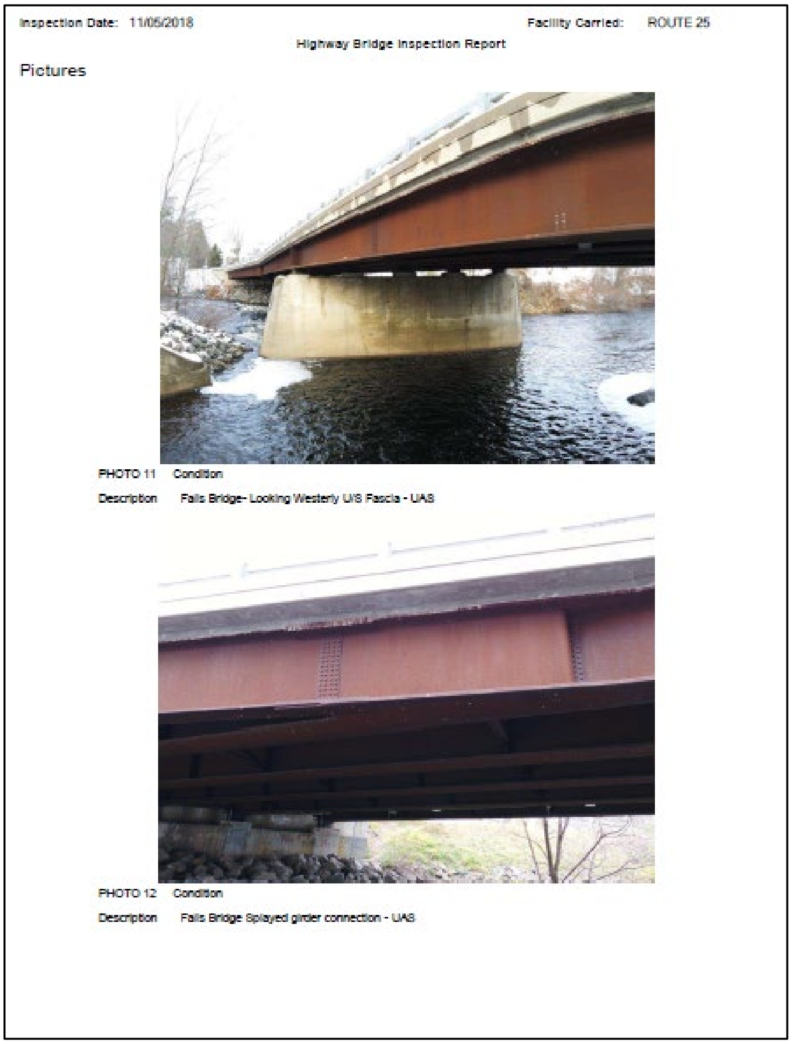


Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Figure 105. Photo. Image 27, fracture critical member and cracked concrete sample taken at 15 ft.

APPENDIX D. EXAMPLE BRIDGE INSPECTION REPORT PAGE INCORPORATING UAS INFORMATION

Figure 106 illustrates how UAS data can be presented in a bridge inspection report. The figure shows a page from a report that presents the results of an inspection on a bridge in Maine performed by a contractor and submitted to the MaineDOT. It should be noted that the only indicator in the report that the inspection team used a UAS is found in the captions of the images, where "UAS" is included in the description. In all other ways, the use of UAS did not alter the inspection reporting process for the bridge owner.



Inspection Date: 11/05/2018 Facility Carried: ROUTE 25

Highway Bridge Inspection Report

Pictures

PHOTO 11 Condition

Description Falls Bridge- Looking Westerly U/S Fascia - UAS

PHOTO 12 Condition

Description Falls Bridge Splayed girder connection - UAS

Figure 106. Photo. Example page from a bridge inspection report in which UAS data are incorporated.

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Recycled
Recyclable