New England Transportation Consortium (NETC)

NETC 20-3

Investigating Thermal Imaging Technologies and Unmanned Aerial Vehicles to Improve Bridge Inspections

Final Report

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- John "Sam" Maxim, Maine Department of Transportation (Technical Committee Chair)
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- Bruce Sylvia, Massachusetts Department of Transportation
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16. Abstract
The overall research objective is to focus on developing UAV-based inspection and analysis protocols using infrared (IR) thermal imaging to determine the existence and extent of concrete delamination, with emphasis on the underside of bridge decks. The research was implemented through 5 tasks:

1. Desk scan of infrared thermal imaging and unmanned aerial vehicle technologies
2. Field demonstration including analysis, reporting, and delamination cross check with traditional methods
3. Development of inspection and analysis protocols
4. Draft final report and Technology Transfer Strategy and Toolbox
5. Final Report

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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 yard	0.765	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short ton (2000 lb)	0.907	megagrams ("metric ton")	Mg ("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 yard	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 yard	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg ("t")	megagrams ("metric ton")	1.103	short ton (2000 lb)	T
		TEMPERATURE (EXACT DEGREES)		
°C	Celsius	1.8C + 32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE AND PRESSURE OR STRESS		
N	newtons	0.225	poundforce	lbf
kPA	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the 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

AGL = Above Ground Level
ASTM = American Society for Testing Materials
ATC = Air Traffic Control
BIN = Bridge Identification Number
CEI = Construction Engineering and Inspection
CFR = Code of Federal Regulations
DOT = Department of Transportation
EMI = Electromagnetic Interference
FAA = Federal Aviation Administration
FHWA = Federal Highway Administration
FOV = Field of View
GB = Gigabyte
GPS = Global Positioning System
GSD = Ground Sample Distance
Hr = Hour
HSA = Hollow Sounding Area
Hz = Hertz
IMU = Internal Measurement Unit
IR = Infrared
IRTI = Infrared Thermal Imaging
Lb = Pound
LF = Linear Feet
LWIR = Long Wave Infrared
LAANC = Low Altitude Authorization and Notification Capability
MB = Megabyte
MOA = Military Operations Area
mK = milliKelvin
mm = millimeter
MP = Megapixels
mph = Miles per hour
MSX – Multi-Spectral Dynamic Imaging
NAS = National Airspace System
NETC = New England Transportation Consortium
NBIS = National Bridge Inspection Standards
NDE = Non-destructive Evaluation
NOTAM = Notice to Airmen
PIP = Picture-in-Picture
RGB = Red, Green, Blue
RPIC = Remote Pilot in Command
ROW = Right of Way
SO = Sensor Operator
SWOT = Strengths, Weaknesses, Opportunities, Threats
Temp = Temperature
TC = Technical Committee
TFR = Temporary Flight Restriction
UAV = Unmanned Aerial Vehicle
UAS = Unmanned Aircraft System
VLOS = Visual Line of Sight
VO = Visual Observer

Executive Summary

This research project "NETC 20-3: Investigating Thermal Imaging Technologies and Unmanned Aerial Vehicles (UAV) to Improve Bridge Inspections" was established by the New England Transportation Consortium (NETC) and administered by the Maine Department of Transportation (DOT). The overall research project is focused on infrared thermal imaging (IRTI) to determine the existence and extent of concrete delamination along the underside of bridge decks. The goal is to increase safety and allow better use of limited staff and resources for state agencies. Both UAV and IRTI are innovative and emerging technologies with the potential to achieve this research objective.

The research project was focused on thermal imaging with drone use as a means of implementation. Drones were not field-tested for non-thermal data collection applications. The research project focused on commercially available products and processes to allow for an easier implementation for the New England state transportation agencies. The intent was such that these agencies would be able to implement these technologies with internal staff once given the proper training and guidance.

A desk scan of existing technologies was performed along with an overall Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of each identified UAV and IRTI combination system. Based on the analysis, the Parrot Anafi USA, DJI Matrice 210 with Zenmuse XT2, and Skydio X2 were selected for field -testing. AECOM also selected the Flir C5, Flir E8, Flir E86, Flir E96, Seek Shot Pro, and Fluke TiX580 handheld thermal cameras for field-testing.

Field-testing was performed at five bridges in Massachusetts and Rhode Island. The test bridges were selected based on the anticipated amount of concrete delamination and ease of access for traditional inspection with hammer sounding and access equipment as well as for drone operations. There were several methodologies used during field-testing. Handheld thermal cameras were used at three of the bridge sites to determine ideal weather and temperature conditions and verify whether the handheld cameras could verify previous inspection findings along with a traditional manual sounding verification. Drone-mounted thermal cameras were used at two of the bridge sites to determine success rates of delamination detection compared to a traditional inspection cross check.

The field-testing concluded that varying degrees of delamination could be detected using IRTI under the right conditions. However, IRTI can be affected by many factors which can lead to false positive identification, or not detecting the delamination. IRTI should be cross checked against visual imagery whenever possible to reduce the probability of false positives for defects.

The results from the field-testing were used to develop protocols for inspection and analysis. Flow charts were developed to provide guidance on whether handheld or drone-mounted thermal cameras would be most effective as well as anticipated effectiveness of implementation based on bridge material, type, age, and condition. Recommendations for weather and temperature conditions during data collection were also developed.

Drone implementation is also an important topic of discussion included within this research paper. While general drone inspection applications were not included as part of field-testing, this report includes discussion on drone operational planning, deployment, bridge inspection applications, and limitations based on AECOM's experiences implementing drones for different agencies.

1 - Introduction / Background

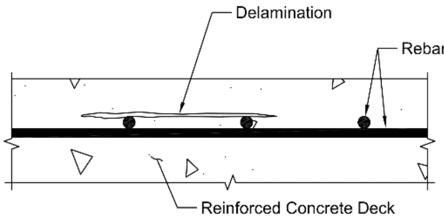


Figure 1 - Concrete Delamination

Bridge inspection is central to any transportation facility's maintenance program. The National Bridge Inspection Standards (NBIS) were established in 1971 following the collapse of the Silver Bridge in West Virginia. The NBIS is governed by Title 23 CFR 650 Subpart C, which defines the NBIS regulation, establishes requirements for inspection procedures, inspection frequency, qualifications of personnel, and implementation of a state bridge inventory. The primary goal of the NBIS bridge inspection program is to accurately identify bridge deficiencies, particularly critical deficiencies that could lead to structural failure or other safety hazards to ensure that bridges are safe for the traveling public [1].

Figure 2 - Removed Concrete from above Highway

One critical safety hazard is concrete delamination along the underside of bridge decks, especially on overpass bridges and on bridges that see pedestrian or boat traffic underneath. Delamination occurs when layers of concrete separate at or near the level of the outermost layer of reinforcing steel (rebar) (refer to Figure 1). The major cause of delamination is expansion of corroding reinforcing steel causing a subsurface fracture plane. This is commonly caused by intrusion of chlorides or salt. Another potential cause is severe overstress in a member [2]. Freeze and thaw cycles can cause this condition to worsen as water freezes within cracks during the winter and expands, causing the crack to widen and allowing more water to enter. Over time, the delaminated concrete will completely separate and create what is known as a spall. Spalling from an overhead concrete element creates a fall hazard that can injure pedestrians or motorists. When located over a highway, spalling concrete is a critical safety concern (refer to Figure 2). Falling concrete can directly cause injury to motorists or create a distraction to drivers resulting in accidents with other vehicles. The roadway is often protected from these areas of delamination through the installation of timber shielding or metal grating between girder bottom flanges. Some agencies, like MassDOT for example, will perform additional inspections of bridges over roadways in the beginning of spring in order to identify and remove any areas of concrete that are at risk of spalling due to the freeze-thaw cycles over the winter.

1.1 - Traditional Methods for Bridge Inspection

Figure 3 - Severe Delamination / Incipient Spall

The traditional methods for inspecting the underside of overpass bridge decks include visual observations and/or manual sounding from underneath by maintenance personnel. This may be done on foot or with the use of access equipment such as a bucket truck or aerial lift. The ability to visually identify delaminations will depend on the size and severity of each individual delamination. Less severe delaminations are commonly referred to as hollow sounding areas and may be indicated by the presences of narrow cracks, efflorescence, and/or rust staining. In the early stages, there may be no visual indication of delamination but limited risk of spalling. Delaminations that are nearing the point of spalling are sometimes referred to as incipient spalls and can be identified by wide cracks, sagging, heavy rust staining, and/or bulging of the concrete (refer to Figure 3). Sometimes visual observations can miss deteriorated areas, especially if the inspection is performed on foot.

Historically, bridge inspectors identify delaminated concrete by manual acoustic methods, commonly referred to as sounding. Sounding uses tools and is based on when the sound from impact changes from a clear ringing sound (sound deck) to a somewhat mute, dull, and hollow sound (delaminated deck) [3]. The delamination has an air pocket which causes a change in the acoustic response. The primary tools for manual sounding that are typically used by bridge inspectors are as follows:

- Chain Drag – A chain or series of short medium weight chains attached to a handle. Inspectors drag the chain(s) along the top of the bridge deck to identify delaminations [2]. The chain drag is limited to the top face of horizontal surfaces.
- Hammer – A tool with a metal head mounted at the end of a handle. Inspectors tap concrete surfaces to identify delaminations [2]. Steel rods or pieces of rebar can be utilized in a similar manner. A hammer can be used on horizontal, overhead, and vertical surfaces.
- Rotary Percussion Tool – Inspectors utilize a rotary percussion tool which consists of two gear-toothed wheels attached to an extension pole and handle. The wheels produce a uniform tapping sound as it rolls over the surface [2]. The rotary percussion tool can be used on horizontal, overhead, and vertical surfaces.

Figure 4 - Inspector Hammer Sounding Deck

These sounding methods are effective at identifying concrete delamination but include several draw backs and challenges. These methods require hands-on access and significant time for proper assessment resulting in additional costs for traffic control and potentially access equipment (refer to Figure 4). The documentation of delamination can also be subjective and varies as delaminated areas are generally irregularly shaped and approximated into more regular rectangular shapes by inspectors. The sound of traffic passing may also cause delays or inaccuracies if the inspector cannot adequately hear the sound produced by the sounding method. This can especially be challenging on heavily traveled roadways, like interstate highways. The sound produced by hammer sounding may not be clearly distinguished between delaminated and solid concrete leading to different inspectors delineating the edges of the delamination differently. It is also possible that the bridge geometry or sloped terrain beneath the bridge may limit hands-on access to some areas of the bridge deck for sounding.

1.2 - Thermal Imaging for Concrete Delamination Detection

Infrared (IR) thermography is one method of non-destructive evaluation (NDE) that can be used for identifying concrete delamination. The delamination contains an air pocket which causes a surface temperature variation and can be detected by IRTI. While infrared thermography has been used to detect delaminations along the top of bridge decks since the 1980s, the application along the underside of bridges is a relatively new endeavor [3]. This research project sought to provide data to determine the effectiveness of delamination detection along the underside of bridges with a focus on accurately identifying delaminations compared to traditional inspection methods.

Figure 5 - Van Equipped with IR Sensor

Infrared thermography is the collection and analysis of infrared electromagnetic radiation emitted by objects which is translated to surface temperature readings through software allowing the inspector to detect variations in temperature. Generally, infrared thermography only captures surface measurements. The infrared spectrum is divided into short wave, mid wave, and long wave, based on the wavelength. Infrared cameras are only capable of detecting infrared radiation within one of the subdivided bands. Long wave infrared (LWIR), which spans between 7.5 micrometers (µm) and 14 µm, is the most common wavelength band and is utilized for concrete delamination detection. Thermal cameras can be handheld, vehicle mounted, drone-mounted, or mounted on manned aircraft (refer to Figure 5).

In the specific application of concrete delamination detection, differences in the surface temperatures of the concrete, translated from thermal radiation, allows the inference of subsurface delaminations or defects. An infrared sensor can be used to locate delaminated areas by observing the surface temperature difference between delaminated areas and solid concrete which exists when the bridge deck is warmed. The basic theory is that heat conduction through the concrete is altered if a delamination is present. Trapped air in a delamination acts as an insulator, permitting the concrete above the delamination to change temperature faster than the surrounding, more massive concrete. When there are no internal defects, heat flow through the deck is relatively uniform [2].

For a topside thermal survey, ASTM-D-4788 "Standard Test Method for Detecting Delamination in Bridge Decks Using Infrared Thermography" provides guidelines for data collection and analysis [4]. The required temperature difference is primarily driven by direct sunlight with the survey taking place between the hours of 9:00 am and 3:00 pm in order to allow enough time for the sun to heat the deck and to minimize shadows from adjacent features. Temperature and weather conditions for topside data collection shall be [4]:

- Greater than 32° Fahrenheit
- Minimal cloud cover
- Winds less than 30 mph
- Deck must be dry for at least 24 hours prior to testing

Thermal surveys along the underside of bridge decks are based upon the same premise as topside applications with the biggest difference being the source of temperature change in the deck. The temperature change in the bridge deck is driven by changes in the ambient air temperature rather than the sun. Because of this, surveys on the underside of a bridge deck aren't dependent on direct sunlight but rather on large swings of the ambient air temperature. The research project attempted to determine the required temperature swings and weather conditions for successful implementation of thermal imaging for underside of deck delamination detection. Refer to Section 3.3 – Thermal Inspection and Analysis Protocols for discussion on the weather and temperature recommendations.

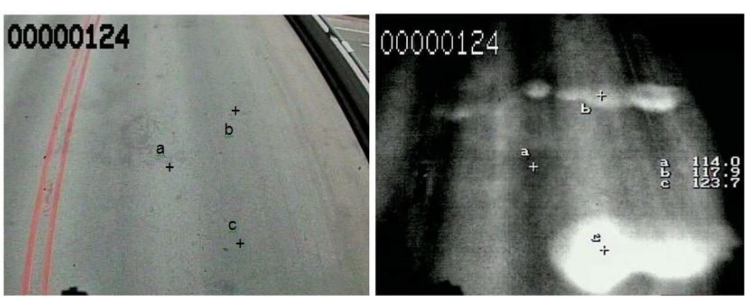


Figure 6 - Top of Deck Visual and IR Imagery

For topside and underside thermal surveys, a real-life visual control image of the bridge deck surface should be captured and utilized during data analysis (refer to Figure 6). Temperature variations can be caused by many factors. These include concrete spalling, discoloration, patching, tar, sand/debris accumulation, uneven heating due to traffic, skid marks, shadows, water, or other anomalies. These irregularities can be misinterpreted as delaminations by inexperienced staff. The real-life visual imagery provides a cross-check for these irregularities to reduce the likelihood of false positive identification. During the course of this research project, the team also experienced false positive detection along the underside of the deck. Additional discussion on false positives for underside detection of delamination is included in Section 3.2.2 - Initial Conclusions.

Due to the potential for false positive identification of delamination, topside thermal surveys generally include field confirmation. Field confirmation of the thermal data primarily consists of two methods: sounding suspected areas of delamination or concrete coring. Both methods of field confirmation are more difficult along the underside of bridge decks and would likely require the use of access equipment such as a bucket truck or aerial lift.

1.3 - Unmanned Aircraft System (UAS)

Unmanned aircraft systems (UAS), which are commonly referred to as UAV or drones, are an emerging technology that is receiving a lot of attention for potential application in bridge inspection. Various public agencies, consulting firms, universities, and private drone manufacturers are performing pilot studies and exploring potential bridge inspection use cases.

This research project focused on drones as a means for thermal data collection. Drones were not field-tested for non-thermal data collection applications. Recognizing the potential benefits of drone implementation with visual sensors, this report includes discussion on drone applications and guidelines based on AECOM's experience utilizing drones for bridge inspection work (refer to Figure 7). Refer to Section 3.4 – General Drone Protocols.

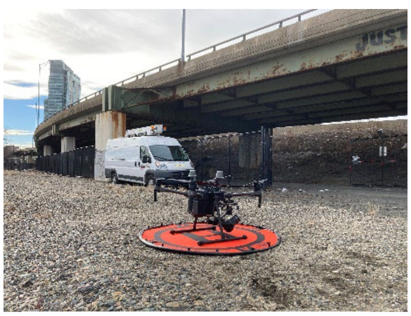


Figure 7 - Drone Bridge Inspection

Commercial drone operations are regulated by 14 CFR Part 107 which was established in 2016 [5]. These regulations govern all commercial operations but can be waived for specific operations by the Federal Aviation Administration (FAA) if it is shown that the operation can be safely completed. All FAA regulations will need to be followed while performing any UAS bridge inspection unless a waiver has been received from the FAA. It is critical that all UAS pilots involved in bridge inspection are familiar with these regulations. The FAA is continually reviewing and reflecting on current regulations based on changes in drone technology and usage, UAS waiver and authorization requests, and feedback from operators and agencies. It is anticipated that the regulations for Part 107 will continue to change over time.

Drones have different operating parameters and capabilities which means that each type will have different strengths and weaknesses. No single drone will fit all situations. It is important that the limitations of each drone are understood by the staff involved in any UAS operation. The biggest constraint for the use of any drone for bridge inspection is the need for the drone sensor to look upwards. Many consumer and commercial drones are primarily limited to downward or forward-facing views, limiting their effectiveness for bridge inspection. The ideal drone for bridge inspection would be able to look fully upwards to easily view the underside of the bridge deck and superstructure.

Drones, including the sensors they carry, only serve as a data collection tool. Different drones and sensors will collect different types of data and with varying quality. The bridge inspector will need to decide whether the data quality is acceptable based on the specific requirements of each task.

The use of UAS for bridge inspection is one of the more challenging applications of this innovative technology. Drones present a few challenges related to flight underneath and around bridges. The first challenge is flight stability. The majority of commercially available drones are manufactured to rely on the global positioning system (GPS) for flight stability. Bridge inspections require flight directly underneath bridges which can hinder GPS connectivity and require direct manual flight of the drone, which can remove safety features like return-to-home functionality in the event of a lost link between the drone and controller. The stability can also be worsened by strong and varying wind currents and eddies forming along the bridge. Steel bridges can create electromagnetic interference (EMI) which needs to be a consideration for flight operations as well.

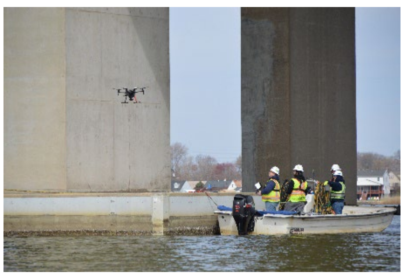


Figure 8 - UAS Operation from Boat

Another challenge is the requirement to maintain visual line of sight (VLOS) of the UAV unless an FAA waiver has previously been granted. Obstructions to maintaining VLOS include the bridge piers as well as portions of the bridge superstructure. Depending on the bridge configuration and adjacent ground features, the flight crew may need to include multiple visual observers (VOs) at different locations, the flight crew may need to change launch positions multiple times, or the drone may need to launch from a boat if the bridge is over water (refer to Figure 8).

2 - Purpose and Scope

2.1 - Research Objectives and Results

The overall research objective is to develop UAV-based inspection and analysis protocols using IRTI to determine the existence and extent of concrete delamination, with emphasis on the underside of bridge decks. The request for proposal outlined the following questions to address the research objective as well as responses resulting from the research project:

1. **Can IRTI technology be used effectively** to identify concrete delamination, especially on the underside of bridge decks where the concrete surface thermal differences may be only subtle due to very little exposure to direct sunlight? What type of thermal resolution is required? Sensor images will need to be “ground-truthed” with actual measured delamination from tried-and-true methods. Also is there sensor equipment that can be used in handheld operation and attached to drones for flight operations?

Yes, thermal imaging technology can identify concrete delamination along the underside of bridge decks. Delamination detection along the underside of bridge decks relies upon ambient air temperature swings. However, bridge inspectors need to be aware of the limitations of thermal imaging for this application. These limitations are as follows:

- Thermal imaging may not show the full size of the delamination
- Thermal imaging can not identify the severity of the delamination (i.e. minor hollow sounding area versus incipient spall)
- Small, minor, or deeper delaminations may not be consistently identified
- Temperature variations shown by thermal imaging can be caused by a variety of factors which can lead to false positive identification
- Inspectors need to be trained to effectively utilize these technologies and correctly interpret the thermal imagery

Based on the results from the research project, AECOM recommends a minimum of a 10-degree temperature swing for handheld thermal cameras and 15-degree temperature swing for drone-mounted thermal cameras. Periods of rainfall should be avoided for thermal data collection; no rain at least 48 hours prior is recommended. Other atmospheric conditions such as dew point and humidity did not appear to influence the likelihood of detection.

The specific thermal resolution required is dependent upon the distance between the thermal camera and point of interest. The greater the distance, the higher the thermal resolution that will be needed for quality results. Additional guidance is provided in Section 3.3 – Thermal Inspection and Analysis Protocols, beginning on Page 24 and Table 10 on Page 25. AECOM geared the desk scan of the research project towards easy to implement commercially available systems but not individual thermal sensors that could be both mounted to a drone and used handheld.

2. **What type of drone hardware,** Camera Specifications, Camera Mountings and Testing Attachments would provide the most cost-effective benefit for each type of data capture? This question will be answered through surveys and test trials of different UAVs. For optimal information gathering, it is envisioned that several technologies will be concurrently employed, and a significant outcome of the work will be an assessment of the relative value and optimum combination of technologies. (e.g. drone and infrared imaging systems).

AECOM's field-testing of equipment included handheld and drone-mounted technologies including six handheld thermal cameras and three drone-mounted thermal camera systems. Based on the results of the field-testing, the Flir E96 and Matrice 210/300 with Zenmuse XT2 are the recommended systems for implementation. Guidance on whether to utilize handheld or drone-mounted systems is included in Section 3.3 – Thermal Inspection and Analysis Protocols, beginning on Page 24, specifically Figure 21 (Page 24) and Table 9 (Page 25).

3. **What data storage and retrieval systems** and hardware are required for managing and easily re-using the potentially enormous volume of digitized information captured? Data storage and data transfer technologies make this a relatively simple problem. However, universal data sharing formats will need to be established early on.

Flir thermal cameras use radiometric JPEG files, commonly notated as R_JPEG. This file format captures and stores temperature data so that Flir thermal processing software will be able to analyze and edit thermal images. Additionally, the radiometric JPEG file is treated as a standard JPEG file by other software which allows users to view the gradient thermal image with most standard software packages and devices allowing easy sharing of data between users. The focus of the research project was on implementing thermal imaging as another bridge inspection tool. The intent was for thermal imagery to be captured similar to regular visual imagery showing defects in a routine inspection. For this approach, data storage considerations should be relatively inconsequential as radiometric JPEGS are typically smaller in size than files from a 16-megapixel (MP) point and shoot camera.

4. **What software** is available or will require development to efficiently process the captured data for human inspection and evaluation? Many generic systems of machine learning (including computer vision) are available and as such it is relatively easy to develop and train prototype systems. Once prototypes are tested, they can be turned into application-specific codes with an interface appropriate for field use.

Based on the relatively new implementation of thermal imaging for delamination detection along the underside of bridge decks, AECOM focused the research project on accuracy of detection rather than implementation of machine learning or artificial intelligence for defect identification. These processes, while potentially useful for increasing efficiency, need to be built upon large volumes of proven and reliable data. Radiometric thermal data can be post-processed after collection on a computer using thermal analysis software. Generally, thermal analysis software is developed by the manufacturer and is available for free. The recommended thermal sensors, the Flir E96 and Zenmuse XT2, are compatible with the Starter (free) version of Flir Thermal Studio.

2.2 - Overview of Tasks

The overall research objective will be achieved by completing five tasks as follows:

- **Task 1:** Conduct a desk scan to identify IRTI and drone technologies that are best suited for use in bridge underside inspections and other needs expressed by the Technical Committee (TC). Include a Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis of each model using a table to display comparative information. Also include any software requirements and compatibility issues. User needs may include concrete delamination determination, cost-effectiveness, data ease-of-use, ease of generating results, etc. Make recommendations on which model(s) would be best suited for inspection needs expressed by TC.
- **Task 2:** Field demonstration of recommended sensor and drone technologies from Task 1. Demonstration will be conducted on [a set number] bridge site(s) coordinated through the TC and will also include data analysis, reporting, and delamination (the existence and extent) cross check with traditional methods. Purchase of equipment will not be allowed as part of this study. Equipment may be leased or rented.
- **Task 3:** Develop UAV-based inspection and analysis protocols using IRTI to determine concrete delamination, with emphasis on the underside of bridge decks. Provide specifications for models selected. Address data storage protocols, identify specific required software, model specific training considerations for pilots and inspectors on software use, cost estimates for selected technology, etc.
- **Task 4:** Draft Final Report and Technology Transfer Strategy and Toolbox includes an Implementation Plan, a Technology Transfer Strategy and Toolbox.
- **Task 5:** Final Report

3 - Research Methods and Results

3.1 - Desk Scan

3.1.1 – Drone-Mounted Thermal Sensors

The desk scan was performed as part of Task 1 of this research project. The equipment desk scan primarily included drone-mounted thermal sensor combinations. The desk scan identified several options for drones with either integrated infrared cameras or swappable gimbal/sensor combinations that were capable of upward views. The desk scan excluded drones that are only equipped with a visual sensor and those that have limited upward viewing capacities.

The following UAV models were selected for evaluation:

- Digital Aerolus Aertos 130 IR
- DJI Matrice 300 with Zenmuse H20T sensor
- DJI Matrice 210 with Zenmuse XT2 sensor
- DJI Matrice 210 with Flir TZ20 sensor
- Flir Ion M440
- Flyability Elios 2
- Parrot Anafi Thermal
- Parrot Anafi USA
- Skydio X2
- Teal Golden Eagle

The desk scan compared numerous characteristics and traits of different drone and thermal sensor combinations. For drone traits, this included order of magnitude base cost, weight and size, ingress protection, maximum payload weight, max wind speed resistance, advertised max flight time, operating temperature range, obstacle avoidance system, and launch capabilities. For sensor and gimbal traits, this included sensor resolution, sensor zoom capabilities, sensor field of view, IR frame rate / frequency, thermal sensitivity, and gimbal pitch range. These traits served as evaluation criteria for each drone and thermal sensor combination. Descriptions and discussion of each criterion is included in the Task 1 Interim Report on Page 9.

An overall SWOT analysis was performed for the identified UAV and IR combination models based on the evaluation criteria. The SWOT analysis tables can be found on Page B-1 of Task 1 Interim Report Appendix B. Several of the key traits and characteristics as part of the SWOT analysis are summarized in Table 1, on the following page. Selected systems are indicated with a green shading within the table. Based on the results of the SWOT analysis, AECOM recommended that the Parrot Anafi USA, DJI Matrice 210 with Zenmuse XT2 sensor, and Skydio X2 be utilized for field-testing (refer to Figure 9 on Page 12). Rationale for these selections based on the SWOT tables are included in Table 2 on Page 12.

Table 1 - Summary Comparison of UAV / IR Models

Summary of Evaluation Factors												
Drone	**Order of Magnitude Base Cost**	**Weight (lb)**	**Size**	**Max Wind Speed Resistance (mph)**	**Max Flight Time (minutes)**	**Launch Capabilities**	**IR Sensor Resolution (pixels)**	**IR Field of View (degrees)**	**Visual Sensor Resolution (megapixels)**	**Frame Rate (Hz)**	**Thermal Sensitivity (mK)**	**Gimbal Pitch Range**
Aertos 130 IR	$38,000	5.95	21" (diag.)	10	10	Hand Launch Capable	320 x 256	34°	15.3	60	60	-90° to +90°
Matrice 300 & H20T	$27,300	13.89	31.89" x 26.38" x 16.93"	33.55	55	Ground Launch Only	640 x 512	40.6°	Wide: 12 Tele: 20	30	<50	-30° to +120°
Matrice 210 & XT2	$27,000	10.82	25.32" (diag.)	26.86	33	Ground Launch Only	640 x 512	45°	12	30	<50	-45° to +130°
Matrice 210 & TZ20	$26,500	10.82	25.32" (diag.)	26.86	33	Ground Launch Only	640 x 512	Wide: 95° Tele: 18°	n/a	30	85	-30° to +120°
Ion M440	$16,500	3.99	22.5" x 22"x 4.9"	23	35	Hand Launch Capable	320 x 256	34°	12	60	<60	Not Provided
Elios 2	$42,500	3.20	15.75" diam.	14.54	10	Hand Launch Capable	160 x 120	56°	12.3	8.7	<50	-90° to +90°
Anafi Thermal	$2,000	0.69	9.53" x 12.40" x 2.52"	31.07	26	Hand Launch Capable	160 x 120	57°	21	8.7	<50	-90° to +90°
Anafi USA	$7,500	1.00	11.10" x 14.69" x 3.30"	32.88	32	Hand Launch Capable	320 x 256	50°	Wide: 21 Tele: 16	60	<60	-140° to +110
Skydio X2	$16,000	2.92	26.1" x 22.4"	25	35	Hand Launch Capable	320 x 256	24°	12	60	<60	-90° to +90°
Golden Eagle	$15,000	2.30	13.9" (diag.)	25	30	Hand Launch Capable	320 x 256	34°	12.3	60	<60	-135° to +45°

Figure 9 - Field-Tested Drones - Parrot Anafi USA, DJI Matrice 210, and Skydio X2 from left to right

Table 2 - Rationale for Selection of UAV / IR Combinations

Drone	Rationale for Selection
Parrot Anafi USA	Relatively low purchase cost
	Compact and lightweight
	Capable of hand launch and recovery
	IR sensor resolution (320x256) is average for evaluated models
	Visual sensor has most megapixels compared to other evaluated models
	Gimbal has largest pitch range
DJI Matrice 210 with Zenmuse XT2 Sensor	Proven commercial UAV
	Drone has master and assistant capabilities for controllers so the pilot can focus on flying with the sensor operator controlling the sensor
	IR sensor has the highest resolution (640x512) of evaluated models
Skydio X2	Compact and lightweight
	Capable of hand launch and recovery
	IR sensor resolution (320x256) is average for evaluated models
	Collision avoidance system provides greater safety and reduces risk beneath bridges

3.1.2 - Handheld Thermal Cameras

There are numerous handheld IR cameras that are commercially available for a variety of applications. Since many of these IR cameras have similar features and limited variations in their technical specifications, a SWOT analysis was not performed for the handheld IR sensors.

AECOM reviewed commercially available cameras and identified several cameras of varying manufacturers and resolutions for field-testing. Several models manufactured by Teledyne FLIR, LLC of varying resolution were selected to provide comparable data and determine the required resolution for concrete delamination detection. Two models produced by other manufacturers (Seek Thermal and Fluke Corporation) were included to provide comparisons for ease of use and data quality. The traits considered for selection of the handheld sensors are similar to those for the UAV mounted IR sensors.

AECOM recommended field-testing of the Flir C5, Flir E8, Flir E86, Flir E96, Seek Shot Pro, and Fluke Ti480 Pro. While the desk scan recommended the use of a Fluke Ti480 Pro, the specific model was not available for rental during the field-testing. The vendor recommended the use of a Fluke TiX580 as an alternative. This substitution provided similar thermal resolution and specifications to the Ti480 Pro and provided the opportunity to test a different style of camera. Refer to Figure 10.

Figure 10 - Field-Tested Handheld Thermal Cameras

The recommended handheld IR sensors specifications are listed in Table 3 on the following page. The rationale for the selection of these cameras is included in Table 4 on the following page.

Table 3 - Handheld Thermal Cameras Selected for Field-Testing

Manufacturer	Model	Resolution	FOV (degrees)	Frame Rate (Hz)	Thermal Sensitivity (mK)	Purchase Cost
Flir	C5	160 x 120	54°	8.7 Hz	<70	$700
Seek	Shot Pro	320 x 240	57°	<9 Hz	<70	$700
Flir	E8	320 x 240	45° x 34°	9	<60	$2,999*
Flir	E86	464 x 348	42°	30	<30	$10,999
Flir	E96	640 x 480	42°	30	<30	$11,999
~~Fluke~~ **	~~Ti480 Pro~~	~~640 x 480~~	~~34°H x 24°V~~	~~60~~	~~50~~	~~$10,350~~
Fluke	TiX580	640x480	34° x 24°	60	≤50	$21,999

** The Flir E8 is discontinued. The cost included in the table is for the new version, the E8-XT. A vendor that rented the E8-XT was unable to be located.*
*** Fluke Ti480 Pro was recommended to be tested but due to vendor availability the Fluke TiX580 was used instead.*

Table 4 - Rationale for Selection of Handheld Thermal Cameras

Thermal Sensor	Rationale for Selection
Flir C5	Rugged handheld camera that is compact and easy to carry
	Easy implementation for bridge inspection staff
	Low cost
	Lowest IR resolution (160x120) which serves as lower boundary for identifying the required resolution for detection
Seek Shot Pro	Alternative manufacturer and software for comparison
	Rugged handheld camera that is compact and easy to carry
	Easy implementation for bridge inspection staff
	Low cost
	Lower IR resolution (320x240)
Flir E8	Relatively low cost
	Lower IR resolution (320x240)
Flir E86	High performance thermal sensor

	Higher IR resolution (464x348)
Flir E96	High performance thermal sensor
	Highest IR resolution (640x480)
Fluke Ti480 Pro *	Alternative manufacturer and software for comparison
	Highest IR resolution (640x480)
	Capable of stitching images to create 1280x960 images

** Fluke Ti480 Pro was recommended to be tested but due to vendor availability the Fluke TiX580 was used instead. The rational for the Fluke Ti480 Pro are also applicable for the Fluke TiX580.*

3.2 – Field-Testing and Analysis

Task 2 for this research project included field demonstration of commercially available handheld thermal cameras and drone technologies recommended as part of the Task 1 Interim Report. The field-testing and analysis was focused on the ability of thermal cameras to identify concrete delamination along the underside of bridge decks with the use of drones as a means of data collection. Refer to the Task 2 Interim Report for detailed information on data collection and analysis.

Several models of handheld thermal cameras were utilized for this research project, including the Flir E96, Flir E86, Flir E8, Flir C5, Fluke TiX580, and Seek Shot Pro. The drones included the Parrot Anafi USA, Skydio X2, DJI Matrice 210 V2 with Zenmuse XT2, and DJI Matrice 300 with Zenmuse XT2. Observations made during field-testing are discussed in the Task 2 Interim Report on Pages 1 through 18.

Five bridges, limited to one or two spans per bridge, were identified for field-testing and data collection for this research project. Each bridge received an in-depth inspection utilizing traditional means of access (i.e. bucket truck or aerial lift) and hammer sounding to identify existing delaminations in order to compare thermal data. Different equipment and methodologies were used at each bridge. Methodologies for each bridge are indicated in Table 5. The bridges include:

- Bridge S-17-039 (Bridge Identification Number (BIN) 4E5) carrying Route 28 in Somerville, MA
- Bridge B-16-033 (BIN 4EU) carrying Morrissey Boulevard in Boston, MA
- Bridge 07001 carrying I-195 Westbound in Providence, RI
- Bridge S-24-083 (BIN 114) carrying I-291 Line K Ramp in Springfield, MA
- Bridge B-16-369 (BIN 4RT) carrying I-90 Eastbound Off-Ramp in Boston, MA

Table 5 - Methodologies for Field-Testing at Each Bridge

Methodology	4E5	4EU	07001	114	4RT
Type of Equipment Used	Handheld	Handheld	Handheld	UAV	UAV
Collect repeated thermal imagery of several delaminations over time to determine optimal weather and temperature conditions for data collection	x				
Collect repeated thermal imagery of several delaminations to compare different Flir handheld thermal cameras with varying thermal resolutions	x				
Survey the underside of the deck using handheld thermal cameras to perform a cross check of the traditional inspection	x				
Determine whether handheld thermal cameras could verify previous inspection findings		x	x		
Perform UAV-IR survey to identify delaminations with no pre-existing deficiency locations for comparison with traditional inspection findings				x	x
Capture multiple sets of thermal imagery of all the delaminations identified during the traditional inspection for comparison					x
Review weather conditions and temperatures against the accuracy of the thermal data		x	x	x	x

Due to the extensive data collected during field-testing, discussion on the data analysis is omitted from this report. Refer to the Task 2 Interim Report beginning on Page 33 for information on the bridge condition, methodology, collected data, and analysis.

3.2.1 - General Observations on Recommended Field-Tested Equipment

This section is intended to provide a brief overview of the traits and characteristics of the equipment that was recommended based on field-testing for this research project. Additional discussion for the remaining equipment can be found in the Task 2 Interim Report on Pages 1 through 18. The observations are limited to the use of the equipment itself and does not include discussion on the specific field-testing sites or associated data.

Based on the results of the field-testing, the Flir E96 and Zenmuse XT2 thermal sensors provide the best performance for concrete delamination detection along the underside of bridges (refer to Figures 11 and 12). The Flir E96 provided the best image quality (640x480 thermal resolution) and detection capabilities out of the tested handheld thermal cameras. For the field-tested drone-mounted thermal cameras, the Zenmuse XT2 provided the best quality imagery, detection capability, and flexibility with the radiometric sensor. The Zenmuse XT2 can be mounted to the DJI Matrice 210 or DJI Matrice 300. However, during the research project, the camera has since been discontinued. The replacement model, the Zenmuse H20T, while not field-tested, is expected to perform similarly to the XT2. While the protocols for implementation will have slightly different steps for this camera, the overall recommendations and procedures will be the same. Tables 6 through 8 on Pages 17 and 18 show several positive and negative observations from field-testing.

Figure 11 - Flir E96

Figure 12 - Zenmuse XT2

Table 6 - Flir E96 Observations

Flir E96 Observations	
Positive	**Negative**
Best thermal resolution and quality	Higher cost than other tested models
Swappable lenses allow flexibility to choose best field of view based on bridge height	Additional lenses cost extra
Touch screen and manual tactile controls allow for easy modification of settings	Swapping lenses in field can result in dirt/debris entering sensor and degrading image quality
1-Touch Level/Span allows automatic adjustment of level to provide best possible data by touching the screen	Size of camera means that it would not be able to be used simultaneously with other inspection tasks
Pistol-grip allows for one handed operation	Camera can get heavy for extended periods
Laser distance measure helps improve focus of images and can be used to verify what is being viewed since the red dot is visible	
Laser distance measure allows better data quality capture during night and low light conditions	
Swappable batteries allow for extended use	
R_JPEG (editable radiometric jpeg) files are viewable by standard computer software	

Table 7 - DJI Matrice 210 with Zenmuse XT2 Observations

DJI Matrice 210 with Zenmuse XT2 Observations	
Positive	**Negative**
Drone allows for two controllers (one for pilot and one for sensor operator)	Sensor needs to be mounted to face upward or downward – less flexibility during individual flights
Interchangeable sensors allow for flexibility based on operational needs	Size of drone makes flights under low clearance bridges (<18’) high risk and more prohibitive
Weatherproof (capable of flying in the rain) and capable of flying in high winds	DJI geofencing can cause additional steps during planning and coordination phases
XT2 camera is radiometric and can be post-processed	Drone is large and bulky, making transportation more difficult
Drone controller is capable of displaying sensor feed to television screen through HDMI	Matrice 210 is no longer being supported by DJI with no new sensors being made for this model of drone and existing sensors becoming hard to find
Obstacle avoidance sensors along front, bottom, and top of drone which offer some collision avoidance	XT2 sensor does not allow manual setting of the temperature span (temperature range being viewed) but it can be adjusted after flight operations on the computer
	Drone needs clear, open, flat surface to launch and land

Table 8 - DJI Matrice 300 with Zenmuse XT2 Observations

DJI Matrice 300 with Zenmuse XT2 Observations	
Positive	**Negative**
Drone allows for two controllers (one for pilot and one for sensor operator). Pilot control and roles can be swapped during flight	Sensor needs to be mounted to face upward or downward – less flexibility during individual flights
Interchangeable sensors allow for flexibility based on operational needs	Size of drone makes flights under low clearance bridges (<18’) high risk and more prohibitive
Weatherproof (capable of flying in the rain) and can fly stable in high winds	DJI geofencing can cause additional steps during planning and coordination phases
XT2 camera is radiometric and can be post-processed	Drone is large and bulky, making transportation more difficult
Long battery life (+/- 45 minutes with XT2)	Drone needs clear, open, flat surface to launch and land
Drone has directional obstacle sensors on each side of the drone that can be customized to set minimum distances	XT2 sensor does not allow manual setting of the temperature span (temperature range being viewed) but it can be adjusted after flight operations on the computer
Drone controller is capable of displaying sensor feed to television screen through HDMI	Drone controller screen can be difficult to see in the field with glare

3.2.2 - Initial Conclusions
This section provides a summary of discussion related to the field-testing and data analysis. The full discussion as well as example thermal imagery is included in the Task 2 Interim Report beginning on Page 19.

The field-testing and data analysis included capturing thermal imagery of varying degrees of delamination along the underside of bridge decks. Assuming that the data collection period has adequate weather and temperature conditions, thermal imagery is able to detect the following types of deficiencies:

- Minor delaminations detected only through manual sounding (refer to Figure 13).
- Minor delaminations with cracking (refer to Figure 14).
- Delamination without visible separation (refer to Figure 15 on Page 20).
- Delaminations with cracking and visible separation (refer to Figures 16 and 17 on Page 20).
- Delaminations along previous repairs due to voids / overpour (refer to Figure 18 on Page 21).
- Both sound patches and delaminations with patches (refer to Figures 19 and 20 on Page 21).

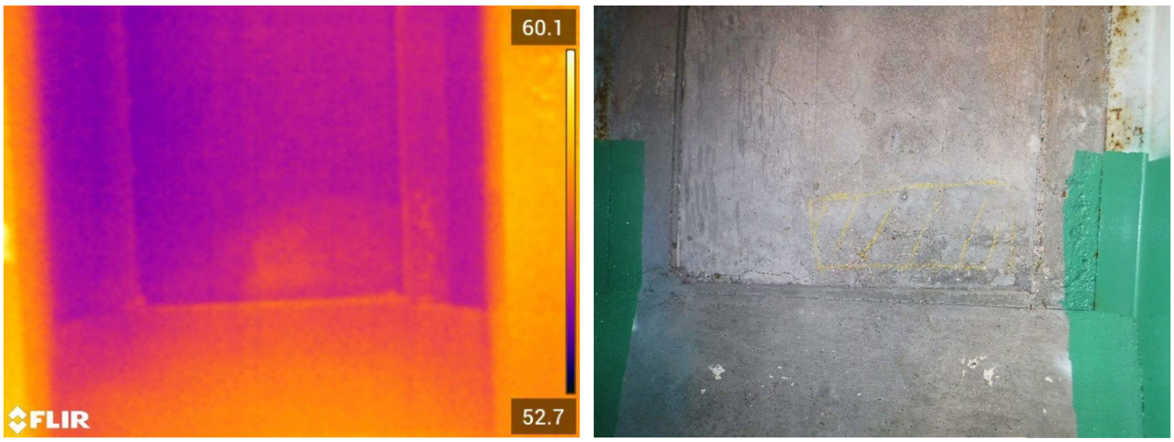


Figure 13 - Minor Delamination

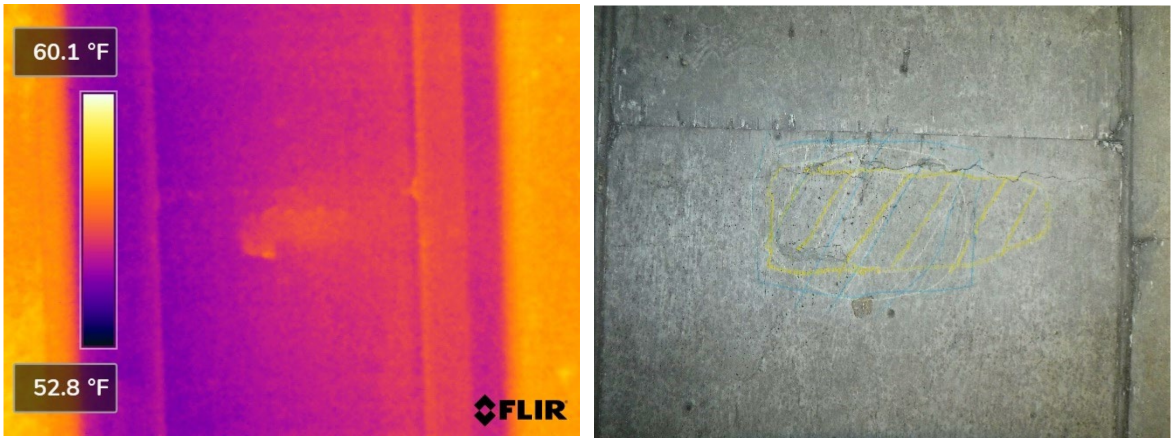


Figure 14 - Delamination with Cracking

Figure 15 - Delamination without Visible Separation

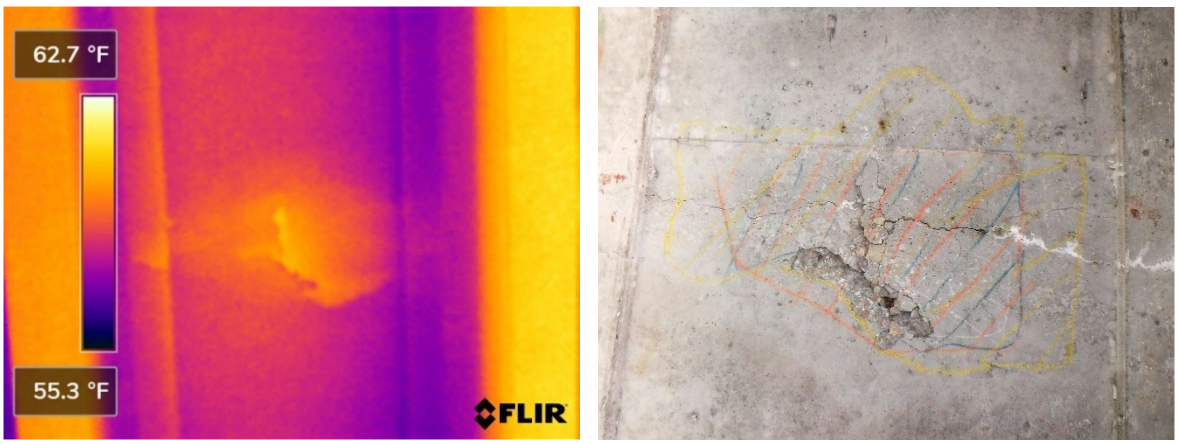


Figure 16 - Delamination with Cracking and Visible Separation

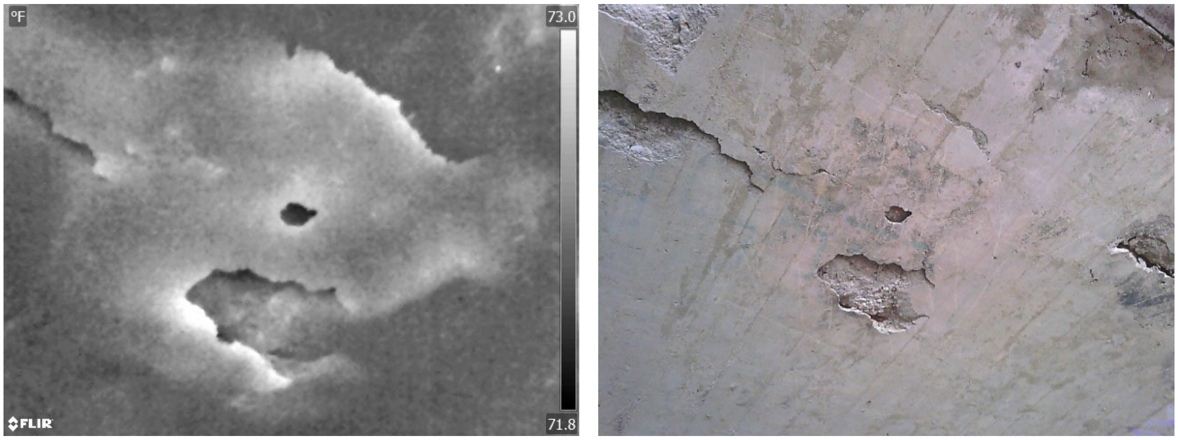


Figure 17 - Delamination with Visible Separation

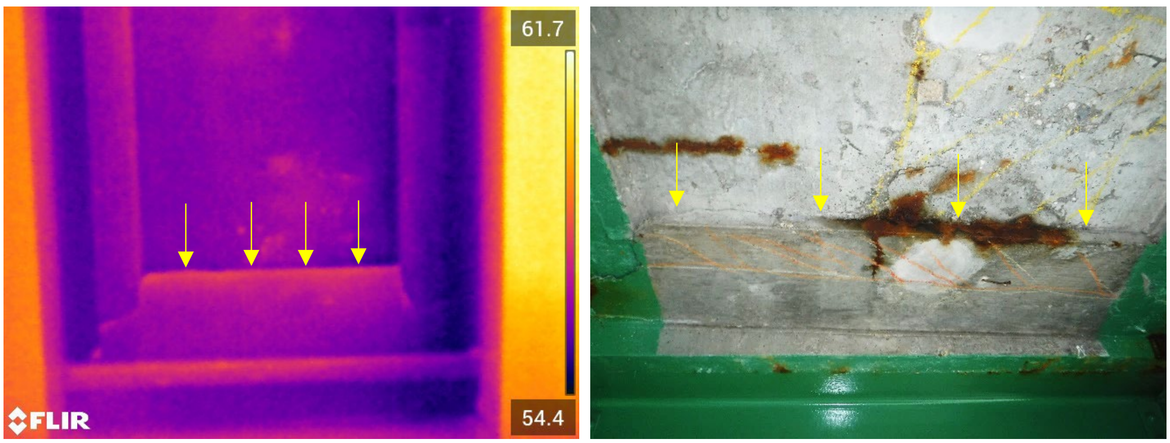


Figure 18 - Delamination along Repair due to Void / Overpour

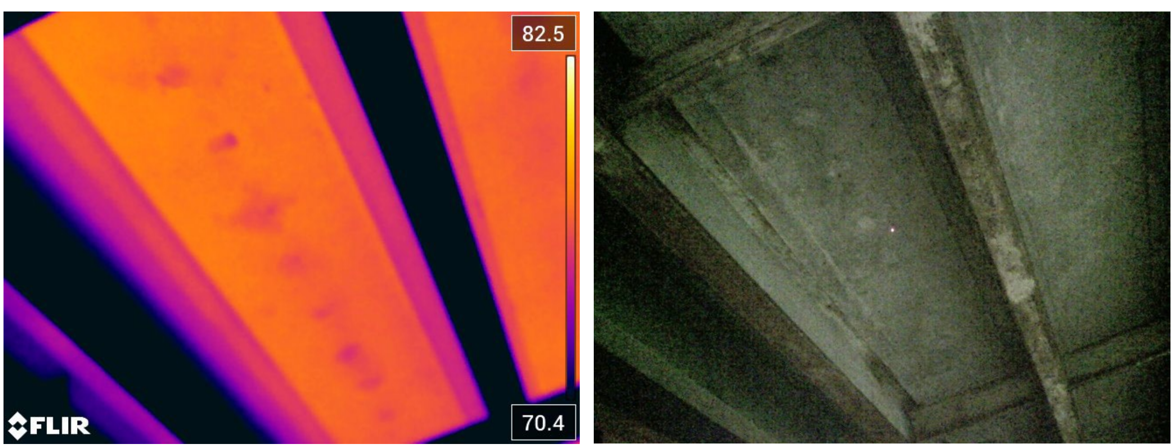


Figure 19 - Sound Patches and Delaminated Patches

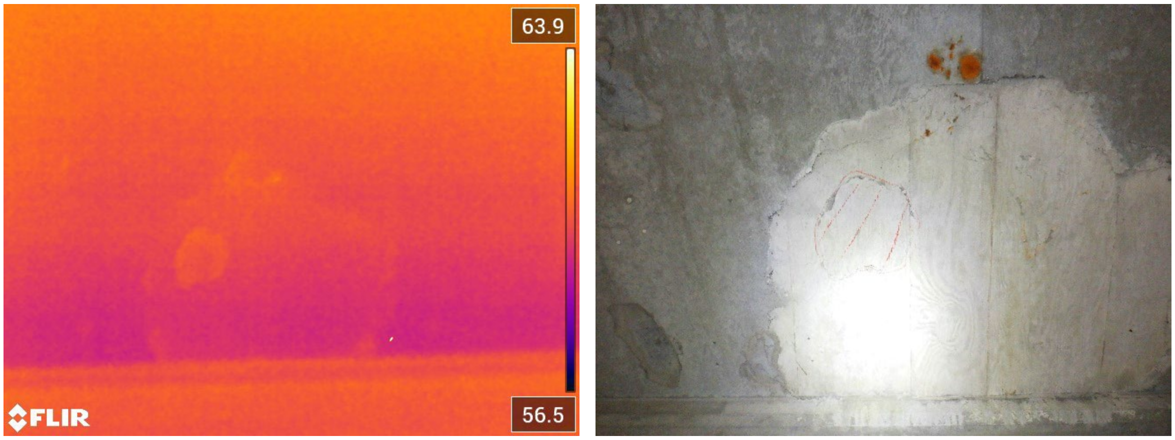


Figure 20 - Delamination within Otherwise Sound Patch

When using automatic settings, thermal cameras will automatically adjust the thermal span based on the objects visible for the sensor. This can cause the thermal span to increase in size which would make delamination detection more difficult as the temperature differences between sound and delaminated concrete are generally within a few degrees of each other. Some factors that can cause an increase in thermal span include:

- Adjacent utilities or light fixtures that generate heat
- Nearby wildlife (such as roosting pigeons) or pedestrians
- Moisture and water leakage
- Visible sky along the bridge fascia or through joints

Temperature readings are affected by many factors which can lead to false positive identification of delamination. For this reason, thermal imagery should be cross checked against visual imagery whenever possible to reduce the probability of false positives for defects. Factors that affect temperature readings include:

- Type of material
- Thickness of material
- Reflective materials
- Angle of data capture
- Paint or other protective coatings
- Shadows
- Surface texture (i.e. honeycombing, scaling, etc.)
- Dirt and debris
- Moisture or water leakage
- Internal voids (box beam and box girder superstructures)

However, cross checks using visual imagery have their own limitations. Handheld thermal camera visual sensors are generally lower megapixels (i.e. 5 MP for Flir E96) which may not provide enough clarity and detail if the bridge has a high vertical clearance. Additionally, the visual imagery of the deck can be washed out from sun glare or underexposed due to the adjacent sky. These are more prevalent near the edges of the deck. Contrast caused by shadows can also result in overexposure of portions of the visible image removing needed detail.

Some key takeaways from the data collection and analysis task include:

- Increased thermal resolution improves the likelihood of concrete delamination detection at farther distances. However, at close distances, lower thermal resolutions perform similar to higher thermal resolutions.
- Handheld thermal cameras offer much more control of data collection settings than drone-mounted thermal cameras thus reducing the need for post-processing and increasing the likelihood of correct defect detection in the field.
- Temperature differentials in thermal imagery caused by delaminations do not always line up with the limits as determined by manual sounding. In some cases, the area shown by the thermal image are smaller than that identified by manual sounding.
- Experience with interpreting thermal imagery is important to reduce the likelihood of false positive identification of defects. False positives can be easily triggered by a variety of factors causing temperature differentials in thermal imagery.
- Thermal imagery should be cross checked with visual imagery whenever possible to reduce the likelihood of false positive identification. However, visual cross checks can be limited based on sun glare, contrast caused by shadows, and overall lighting conditions. Additionally, visual cross checks may only work for delaminations with visible indicators on the surface; it would not work for delaminations that do not have any visible signs on the surface.
- Even under ideal conditions, it is possible that not all delaminations along the underside of bridge decks will be detected by thermal imaging. Delaminations that are minor, small in size, or deeper within the deck may not be detected. However, the thermal data for BINs 114 and 4RT identified more areas of delamination than were noted as part of the most recent bridge inspection reports.

3.3 - Thermal Inspection and Analysis Protocols

The use of a handheld or drone-mounted thermal camera will depend on numerous factors including the time of data collection, bridge height, and features that the bridge spans over. A flow chart and bridge height selection matrix have been developed to help assist in determining whether handheld or drone-mounted will be the more effective method of data collection (refer to Figure 21 below and Table 9 on the following page). A larger version of the flow chart can be found in Appendix A. These are intended to provide guidance only and are not intended to be set-in-stone rules. The decision tree in the flow chart is based on the assumption that the specific bridge site allows compliance with all Part 107 regulations.

Handheld thermal cameras may be easier to implement for state transportation agencies based on the additional costs and training requirements of drone programs. Different agencies and consultants will have different equipment available. Refer to Table 10, on the following page, for a selection matrix for thermal camera resolution compared to the distance to the bridge element.

Discussion of the criteria utilized in the flow charts and bridge selection matrix is discussed in the Task 3 Interim Report beginning on Page 4.

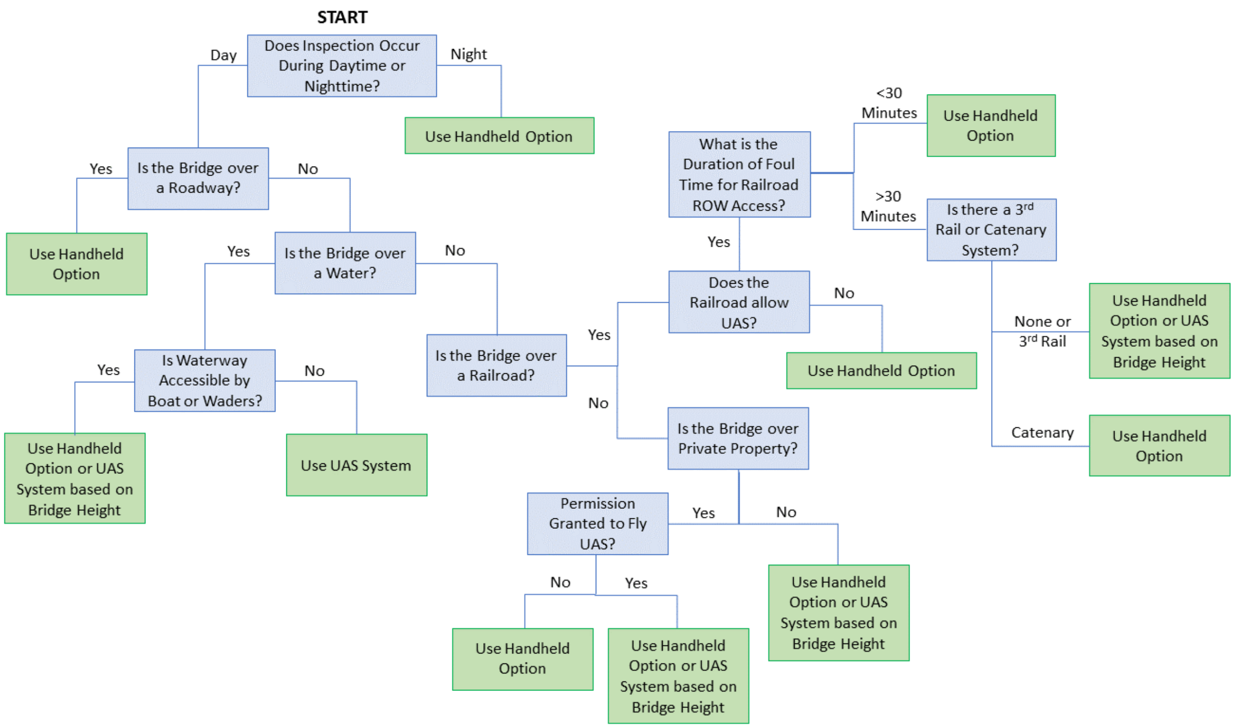


Figure 21 - Equipment Selection Flow Chart

Table 9 - Equipment Selection Matrix Based on Distance

Equipment Selection Matrix Based on Bridge Height				
Distance to Bridge Element	Flir E96			Zenmuse XT2 (640x480, 13mm)
	10mm	17mm	29mm	
10'	✓			
15'	✓			
20'	✓			✓
25'	✓			✓
30'	✓	✓		✓
35'	✓	✓		✓
40'		✓	✓	✓
45'		✓	✓	✓
50'		✓	✓	✓
>50'			✓	✓

Table 10 - Thermal Resolution Based on Distance

Distance to Bridge Element	Thermal Camera Resolution					
	160 x 120	320 x 240	336 x 256	464 x 348	640 x 480	640 x 512
<10'	✓	✓	✓	✓	✓	✓
10'	✓	✓	✓	✓	✓	✓
15'	✓	✓	✓	✓	✓	✓
20'		✓	✓	✓	✓	✓
25'		✓	✓	✓	✓	✓
30'				✓	✓	✓
35'				✓	✓	✓
40'					✓	✓
45'					✓	✓
50'					✓	✓
>50'					✓	✓

3.3.1 - Temperatures and Weather Conditions

3.3.1.1 - Analysis of Temperature and Weather Conditions

The temperature and weather conditions during the Task 2 field-testing have been compiled into summary tables, which can be found as Appendix B. The summary tables are divided into two separate tables based on the type of equipment. These tables only include data for the underside of bridge decks. The following data was omitted from these summary tables:

- Post-processed thermal imagery was omitted for all bridges. Thermal imaging technology would be most efficiently implemented if post-processing is not required. The temperature and weather recommendations are based on the imagery captured from the field and not edited in the office after the fact.
- Washington Bridge (07001) was omitted as the detection included both the deck and superstructure.
- BIN 114 column data was omitted. The column was exposed to direct sunlight which would skew the remaining data that was reliant on ambient air temperature changes.
- BIN 4EU data was only included for the Flir E96. The data for the Flir E8 was omitted to ensure consistency in the detection capabilities of the sensor.
- BIN 4E5 data was omitted for all cameras other than the Flir E96 to ensure consistency in the detection capabilities of the sensor.

Scatter plots were developed from the summary tables based on the percentage of delaminations that were partially and fully detected compared to the temperature change over time. Refer to Figures 22 and 23 on the following page. In general, the temperature change versus delamination detection did not have much correlation when evaluating the 1-hour, 2-hour, and 3-hour temperature changes. The 6-hour temperature changes had a more notable correlation. For the Flir E96, the trend line indicates that 80% of delaminations should be identified with an approximately 8.5-degree temperature change over 6 hours before data collection. For the Zenmuse XT2, the trend line indicates that 80% of delaminations should be identified with an approximately 18-degree temperature change over 6 hours before data collection.

Linear trend lines were added to the plots for visual reference. The R-squared (R^2) regression coefficient value is included within the plots. The R-squared value is generally used for a measure of model goodness of fit and shows the error in % delamination detected relative to total variation in % delamination detected. Because the model is linear, R-squared is also the square of the correlation coefficient which is a measure of the linear relationship between temperature change and % delamination detected. A trendline with a good fit/correlation has R-squared values closest to 1. A trendline with poor fit/no correlation has R-squared values near 0. R-squared values from Figures 22 and 23 are summarized in Table 11.

Table 11 - R-Squared Values for Trendlines

% Detected vs Temp Change Duration	Flir E96	Zenmuse XT2
6 Hour	0.2771	0.6012
3 Hour	0.0686	0.0934
2 Hour	0.0258	0.0045
1 Hour	0.0411	0.2309

Generally, the trend lines are not very good fits and show limited correlation. The detection rates for the Flir E96 at BIN 4E5 varied and did not always correlate to the expected results based on the temperature. For example, there were six days of data collection with a temperature swing of 7 degrees over a 6-hour period. This resulted in 22.73, 95.45, 40.91, 12.50, 91.67, and 45.83 percent detection rates which indicates other factors beyond just temperature change influencing the results. The Zenmuse XT2 trendline had a better fit for a 6-hour period, which can likely be attributed to the smaller amount of data collected and higher variation in temperature change experienced. While not the best fit, the trendlines are utilized to provide some guidance for data collection.

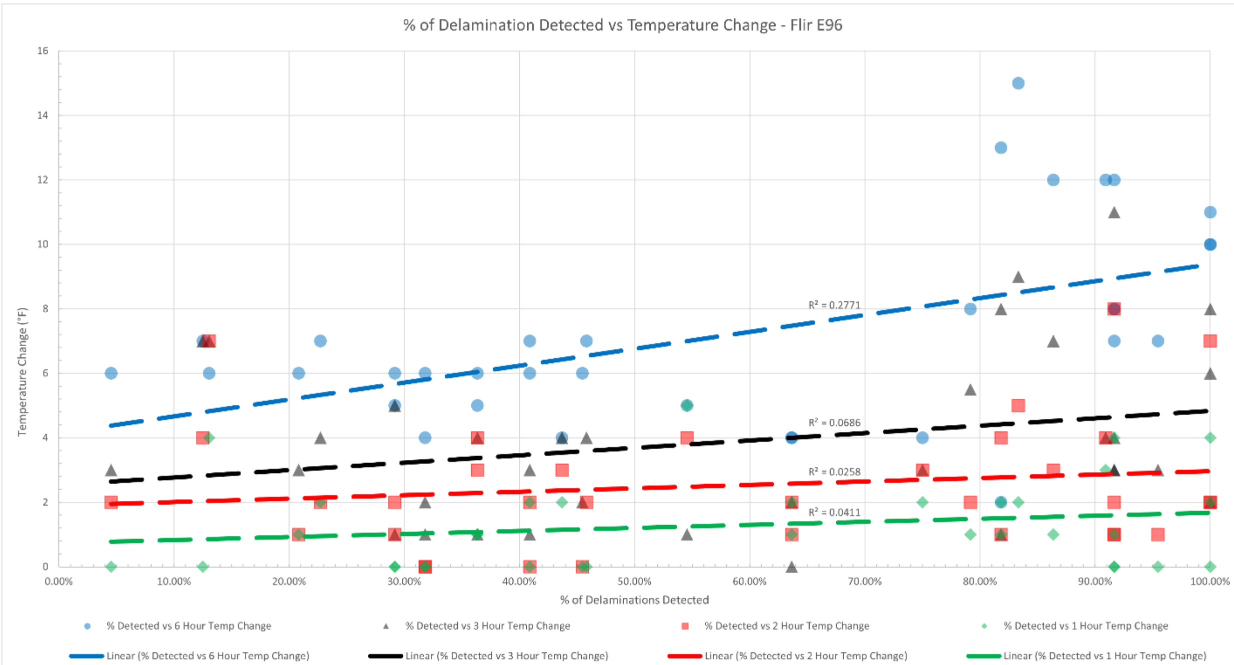


Figure 22 - Delamination Detection versus Temperature Change for Flir E96

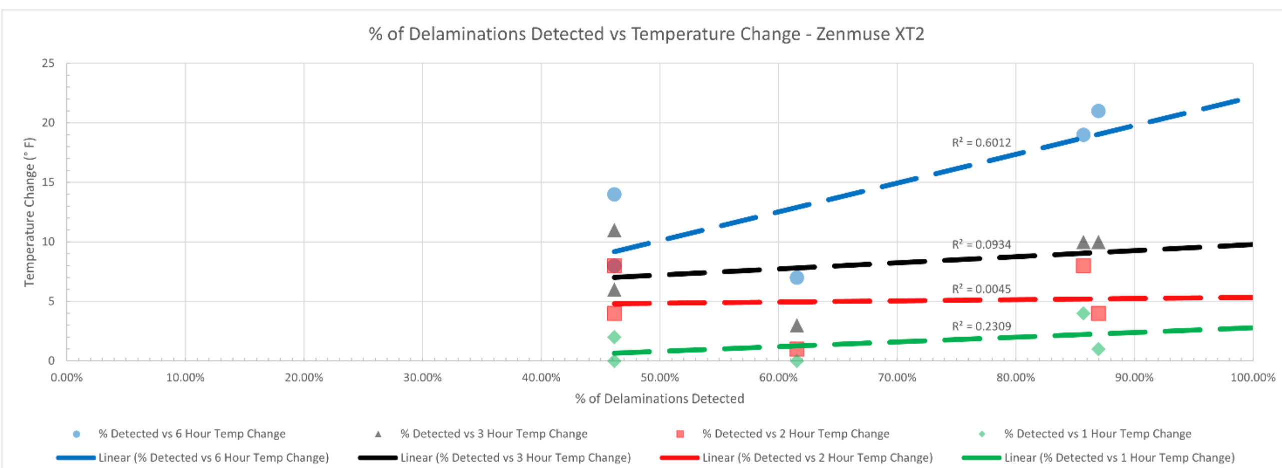


Figure 23 - Delamination Detection versus Temperature Change for Zenmuse XT2

Some potential causes for the differences in the required temperature change for detection between the two recommended thermal cameras include:

- The ability to manually set the temperature span during data collection for handheld cameras which optimizes the ability to identify delaminations. The Zenmuse XT2 is not able to have a manually set temperature range in the field.
- The field data for the Flir E96 included determining detection of known delaminations at various times of day and weather. The detection of these locations was determined visually based on the image gradient. There is potential for bias in positive identifications since it was known that delamination was present.
- The Flir E96 and Zenmuse XT2 were not tested at the same bridges.
- The Zenmuse XT2 was only test at two bridges; BIN 114 had significant delamination. BIN 4RT had minor delaminations. One more day of field-testing was performed at BIN 4RT which may be skewing the results.

3.3.1.2 - Weather and Temperature Recommendations

Based on these summary tables and scatterplots, the recommendations for data collection include:

- Temperature change of at least 10 degrees for handheld and 15 degrees for drone-mounted for the proceeding 6 hours
- No rain at least 48 hours prior
- Wind speeds less than 30 mph for handheld; 15-20 mph for drone-mounted
- No recommendations are included for dew point or humidity. These atmospheric conditions did not appear to influence the likelihood of detection.

Periods after rainfall should be avoided. Water can become trapped in the deck which can skew results. Dampness along the bridge fascia and joints can also influence the data.

The wind speed varied greatly during field-testing and did not appear to have an effect on the number of delaminations detected. However, the field-tested bridges were not in the open and may have been shielded from wind. ASTM D4788 – 03: Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography, which provides the standards for delamination detection along the topside of bridges, indicates that winds shall not exceed 30 mph for testing [4]. This limit shall be considered applicable for the underside of the bridge deck as well. Additionally, depending on the specific drone being used, winds of 15-20 mph may be the cut off for performing the drone flight based on the drone model wind rating.

These recommendations are intended to be guidance. Thermal imagery can still be captured and provide useful information outside of the recommendations. The amount of data currently used is limited, and additional field-testing may result in updated recommendations.

3.3.2 - Recommended Field Inspection Protocols

3.3.2.1 - General Procedure

The use of thermal imaging as an inspection tool is going to be dependent on the application, bridge condition, and temperature swings. In general, radiometric thermal cameras provide the best option for field inspection because the thermal span can be optimized prior to capturing imagery and allow flexibility with the ability to post-process the thermal imagery.

Thermal imaging will take some time for the user(s) to gain familiarity with the technology and the temperature change requirements. While it may be tempting to return to the existing traditional methods after only a few tries, staff should persevere through the initial difficulties with these new technologies.

The use of thermal imaging should meet the guidelines for temperature change and atmospheric conditions discussed earlier in this report.

The following steps are recommended for the Flir E96 thermal camera use:

1. Adjust the settings as follows:
    a) Record photo files as radiometric JPEG files (.R_JPEG)
    b) Set the camera to capture thermal and visual images as separate JPEG files
    c) Set the camera to high gain mode
    d) Set the color palette to white hot
    e) Set the camera to display thermal only (no MSX overlay)
    f) Set the auto focus to be based on the laser distance measure
2. Perform a visual screen of the deck to identify whether any visible delaminations are present:
    a) If delaminations are visibly apparent or have been previously delineated by inspectors, use one as a calibrating location. Adjust the minimum and maximum temperatures to be approximately 8 to 10 degrees Fahrenheit apart. The temperature span should then be adjusted so that the delamination is visible due to the temperature differential.
    b) If the existing delamination is not able to be identified with the optimized thermal span, it is likely that the temperature change is not sufficient for detection. If possible, repeat the process at a later time or date.
    c) If no delaminations are visibly apparent, the temperature span should still be manually set to be approximately 8 to 10 degrees Fahrenheit. The temperature span should be set so that temperature differentials along the deck are identifiable. If possible, the inspector should verify the existence of delamination at an identified temperature differential in the field using either a hammer or rotary percussion tool. Once identified, the temperature span should be further modified to optimize detection based on the delamination.
3. Perform data capture. The Flir E96 includes a feature that will auto adjust the thermal span (portion of temperature range being viewed in camera) when set in manual mode. Touching the screen will cause the camera to automatically shift the midpoint of the thermal span to increase contrast based on the location touched on the screen. The inspector should touch the screen to re-adjust the thermal span for each portion of the element surveyed with a thermal camera.

The following steps are recommended for the Zenmuse XT2 use:

1. Perform all drone protocols regarding planning and site deployment in accordance with Section 3.4 – General Drone Protocols.
2. Position drone so that the thermal camera is not pointed towards the sun.
3. Turn on the drone and let sit for approximately 10 minutes prior to flight to allow the thermal camera to warm up.
4. Adjust the settings as follows:
    1. Record photo files as R_JPEG
    2. Set the camera to capture thermal and visual images as separate JPEG files
    3. Set the camera to high gain mode
    4. Set the color palette to white hot
    5. Set the camera to display picture-in-picture (PIP) mode with the visual and thermal imagery displayed side by side.
5. Verify adequate GPS signal (minimum 10 satellites) and that home point has been established.
6. Ensure clear distance/buffer around drone, launch drone, and perform test of flight controls approximately 10-15 feet above launch point.
7. Perform drone flight and data capture.

Flow charts have been developed in order to assist in determining whether thermal imaging would be an efficient tool for deck, superstructure, and substructure as part of an inspection. The intent of the flow chart is to assist in decision making based on the likelihood of delamination being present. This would help guide staffing in order to assigned bridge inspectors trained for thermal imaging to be assigned to bridges which are most likely to have concrete delamination. Refer to Figures 24 through 26 (Pages 30 and 31). Larger versions of the flow charts can be found in Appendix A. Discussion of the criteria utilized in the flow charts is discussed in the Task 3 Interim Report beginning on Page 12.

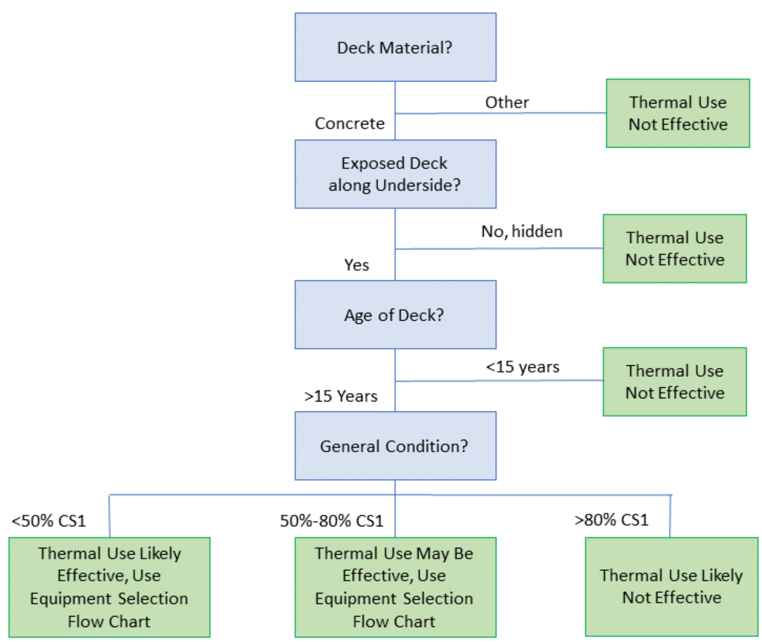


Figure 24 - Flow Chart to Determine Effectiveness for Underside of Bridge Decks

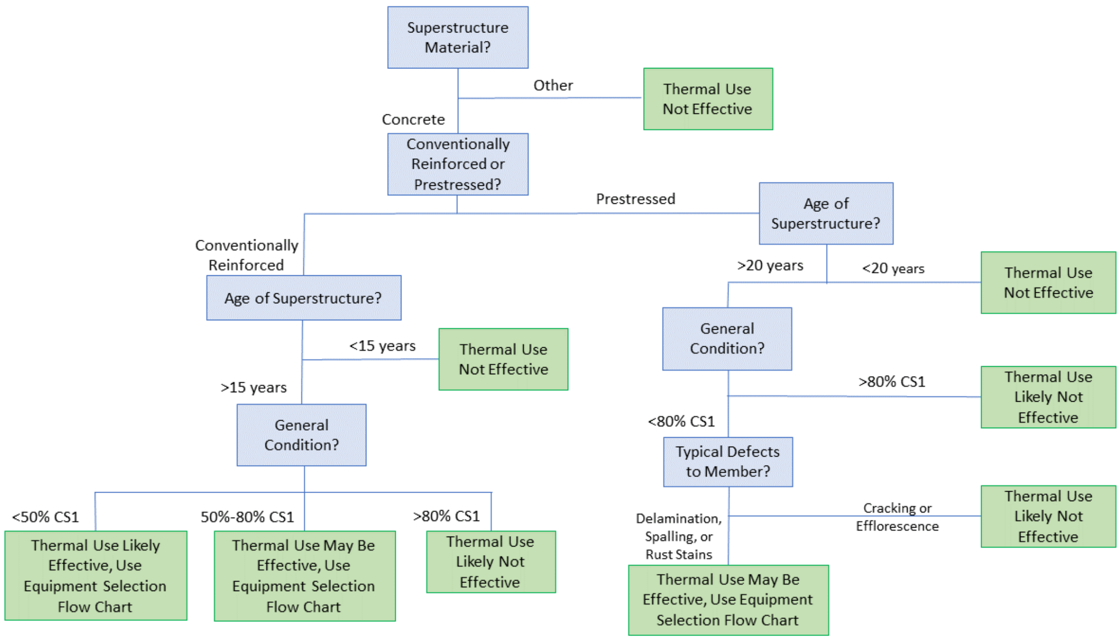


Figure 25 - Flow Chart to Determine Effectiveness for Superstructure Elements

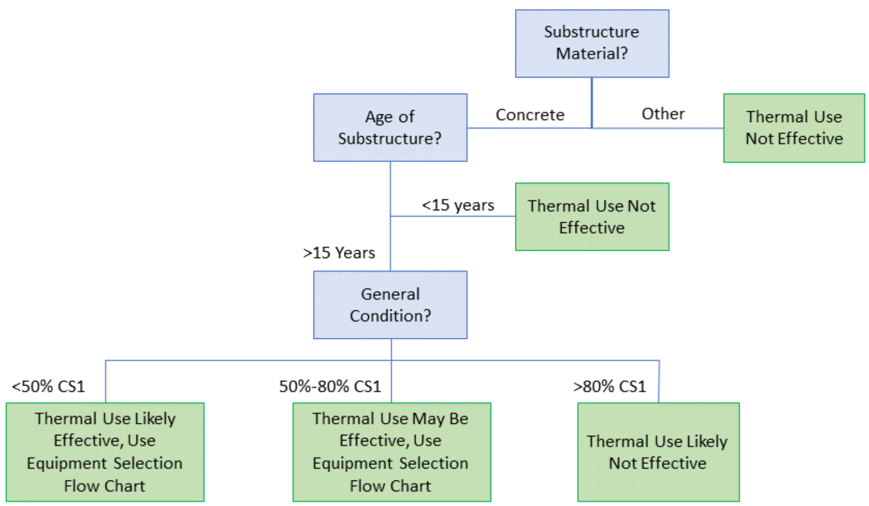


Figure 26 - Flow Chart to Determine Effectiveness for Substructure Elements

3.3.2.2 - Field Applications - National Bridge Inspection Standards (NBIS) Inspection

Thermal cameras can be used as another tool for bridge inspectors. It can be used as a screening tool in order to identify potential delaminations for hands-on access. However, it is important to understand the limitations of the technology, especially when it is being used to inspect a portion of a bridge deck above a roadway carrying the traveling public. There is no guarantee that a thermal camera will identify delaminations and the thermal image will not be able to portray whether the location is a hollow sounding area or an incipient spall.

For NBIS inspection, it is recommended that the thermal camera be utilized as a screening tool to identify locations for sounding when hands-on access is planned or to identify potential locations of delamination if only a visual inspection is being performed. If the inspector identifies a temperature differential that they believe is a delamination but does not verify with sounding, then that should be noted as part of the field notes. This allows future inspections to verify the delamination.

When the drone-mounted thermal camera is being utilized, three crew members should be utilized. The first will be responsible for piloting the drone, the second will control the sensor, and the third will take the field notes either as text descriptions or sketches. The work can be performed with two crew members but there will be much less efficiency in relation to note-taking. The specific method of note taking will depend on the amount of deterioration along the bridge deck. While it may be possible to develop a scaled plan of delamination along the underside of the bridge deck, it likely will not be an efficient method for a NBIS inspection unless detailed underside of deck sketches are included from previous inspections.

3.3.2.3 - Field Applications - Rehabilitation Level Inspection

Data collection for the topside of the bridge deck shall be performed in accordance with ASTM D4788 – 03: Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography [4].

Data collection for the underside of the bridge deck shall be performed in accordance with the temperature and weather recommendations within this report. However, recognizing that the recommendations were made based on limited data, the inspector should repeat data collection, or spot check several locations at a later time to ensure accurate results.

Any suspected delaminations from the thermal imagery should be plotted on a scaled plan of the bridge deck using either a manual or computerized process. This scaled plan can then be used to determine square feet and percentage of delamination.

3.3.2.4 - Field Applications - New Construction

The field-testing performed as part of this research project did not include any new construction. However, thermal cameras may be able to identify voids and delamination related to construction for new structures. Conceptually, voids also include air pockets similar to delamination. If the voids are large enough in plan area, they should be able to be identified with a thermal camera. The thermal camera can be used by construction engineering and inspection (CEI) staff to attempt to identify these areas during construction or by an NBIS inspection team during the initial inventory inspection.

3.3.3 - Thermal Data Analysis

The field-testing as part of Task 2 identified that the following types of deficiencies could be detected:

- Minor delaminations detected only through manual sounding
- Minor delaminations with cracking
- Delaminations without visible separation
- Delaminations with cracking and visible separation
- Delaminations along previous repairs due to voids / overpour
- Sound patches, delaminated patches, and delaminations within patches

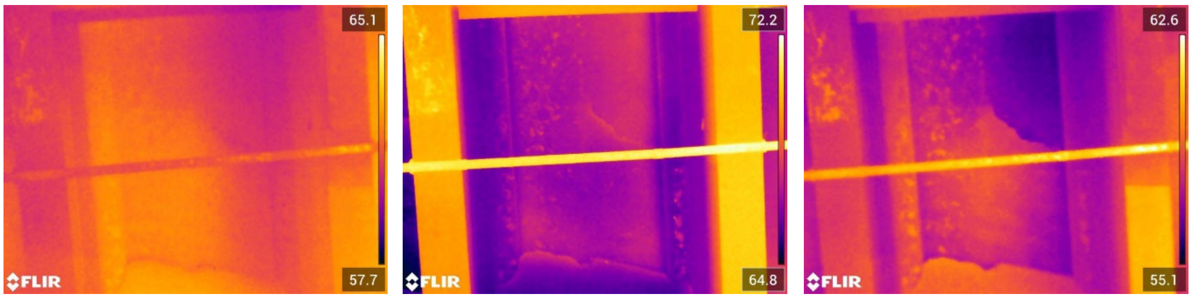


Figure 27 - Variations of Thermal Imagery for BIN 4E5, Location 7

However, the appearance of delaminations in thermal imagery will vary greatly depending on the change in temperature and weather conditions. The repeated thermal imagery of delaminations at BIN 4E5 showed a range of appearances throughout the field-testing. These can include very defined or barely differentiated edges as well as varying amounts of delaminated area having noticeable temperature differential (refer to Figures 27 and 28).

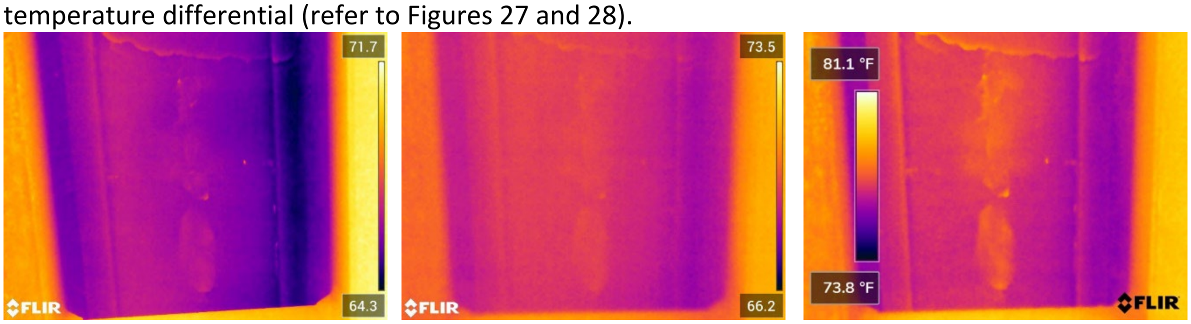


Figure 28 - Variations in Thermal Imagery for BIN 4E5, Location 11

As discussed earlier, the thermal span should be optimized for detection of delamination. Ideally, this is performed prior to data collection so post-processing is not necessary. If the minimum and maximum temperature values are not able to be set in the field, the thermal imagery can be post-processed to incorporate these limits. In general, an 8-to-10-degree temperature span should provide a good starting point for optimizing to detect concrete delamination. Refer to Section 3.3.3.2 – “Thermal Analysis Software Packages” on Page 37 for additional information.

3.3.3.1 - Color Palette

Thermal cameras have different color palettes for viewing thermal data. The use of white hot, or a similar grayscale palette is recommended for use in identifying concrete delamination, especially for drone applications. The other color palettes, such as ironbow, lava, artic, and rainbow feature a wider range of colors which can make it difficult to distinguish the actual amount of temperature difference. White hot includes different shades of gray which are subtler and make it easier to distinguish larger temperature changes (refer to Figure 29). Additionally, with the Zenmuse XT2, the thermal span cannot be manually set which causes the scene to vary as the drone flies along the bridge. This effect is considerably reduced with the white hot color palette.

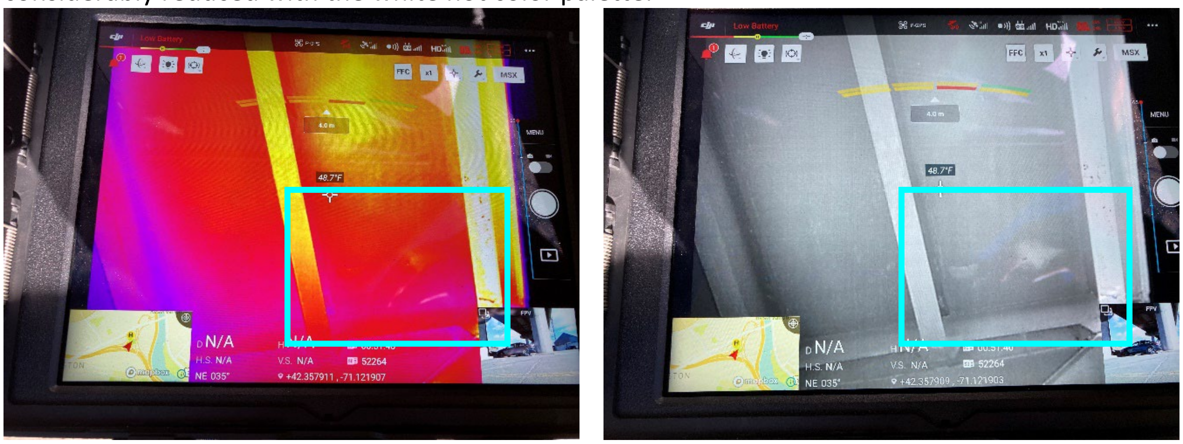
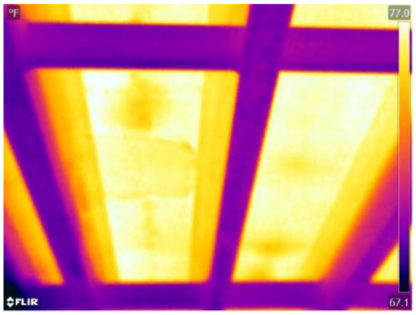


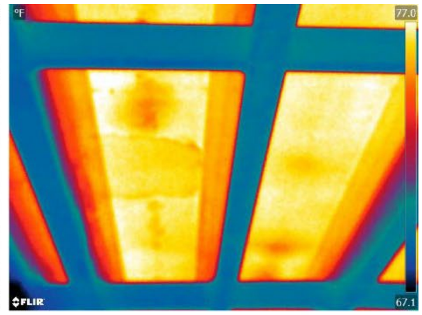
Figure 29 - Screen Shots of Ironbow and White Hot Color Palettes Showing Delamination

Figures 30 (Page 35) and 31 (Page 36) provide several examples of concrete delamination using automatic and manual temperature spans in different color palette.

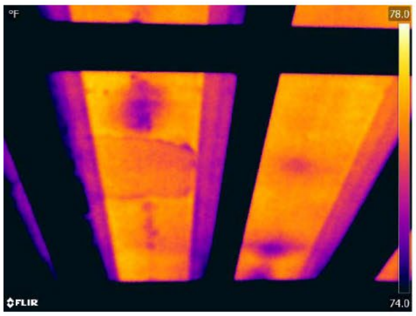


Ironbow Palette, Automatic

Grayscale (White Hot) Palette, Automatic

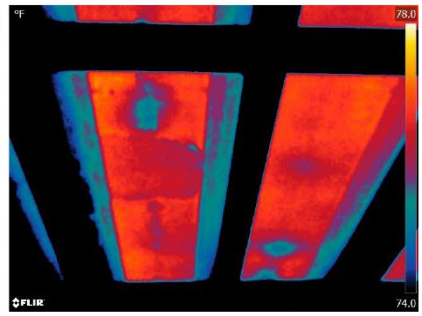


Lava Palette, Automatic

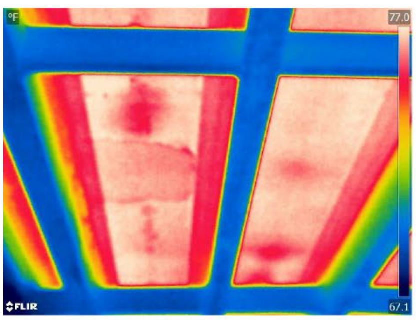


Ironbow Palette, Manual

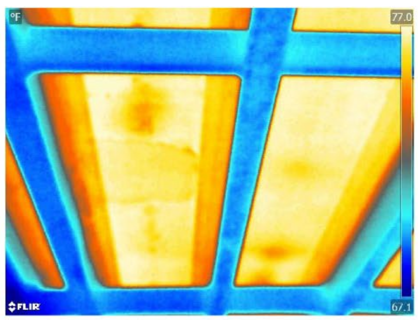
Grayscale (White Hot) Palette, Manual



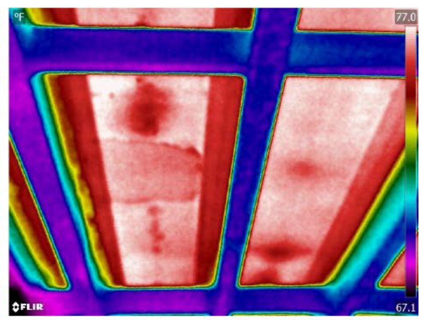
Lava Palette, Manual



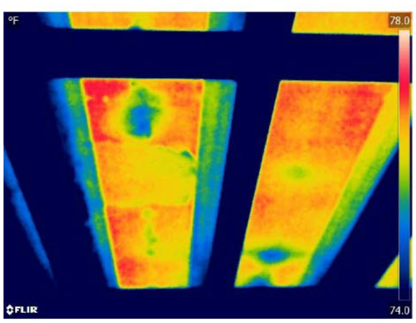
Rainbow Palette, Automatic



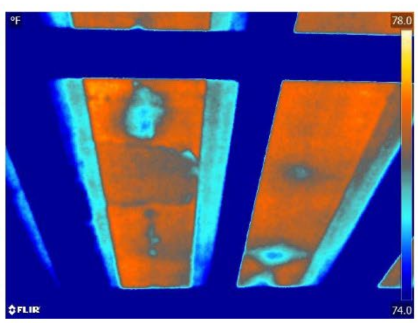
Artic Palette, Automatic



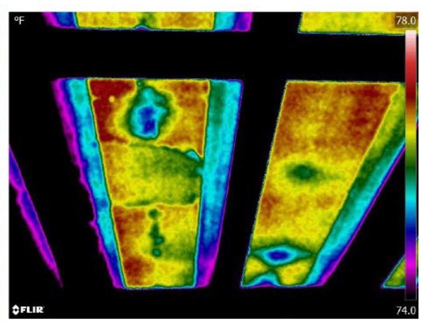
Rainbow High Contrast Palette, Automatic



Rainbow Palette, Manual



Artic Palette, Manual



Rainbow High Contrast Palette, Manual

Figure 30 - Comparison of Color Palettes for Flir E96

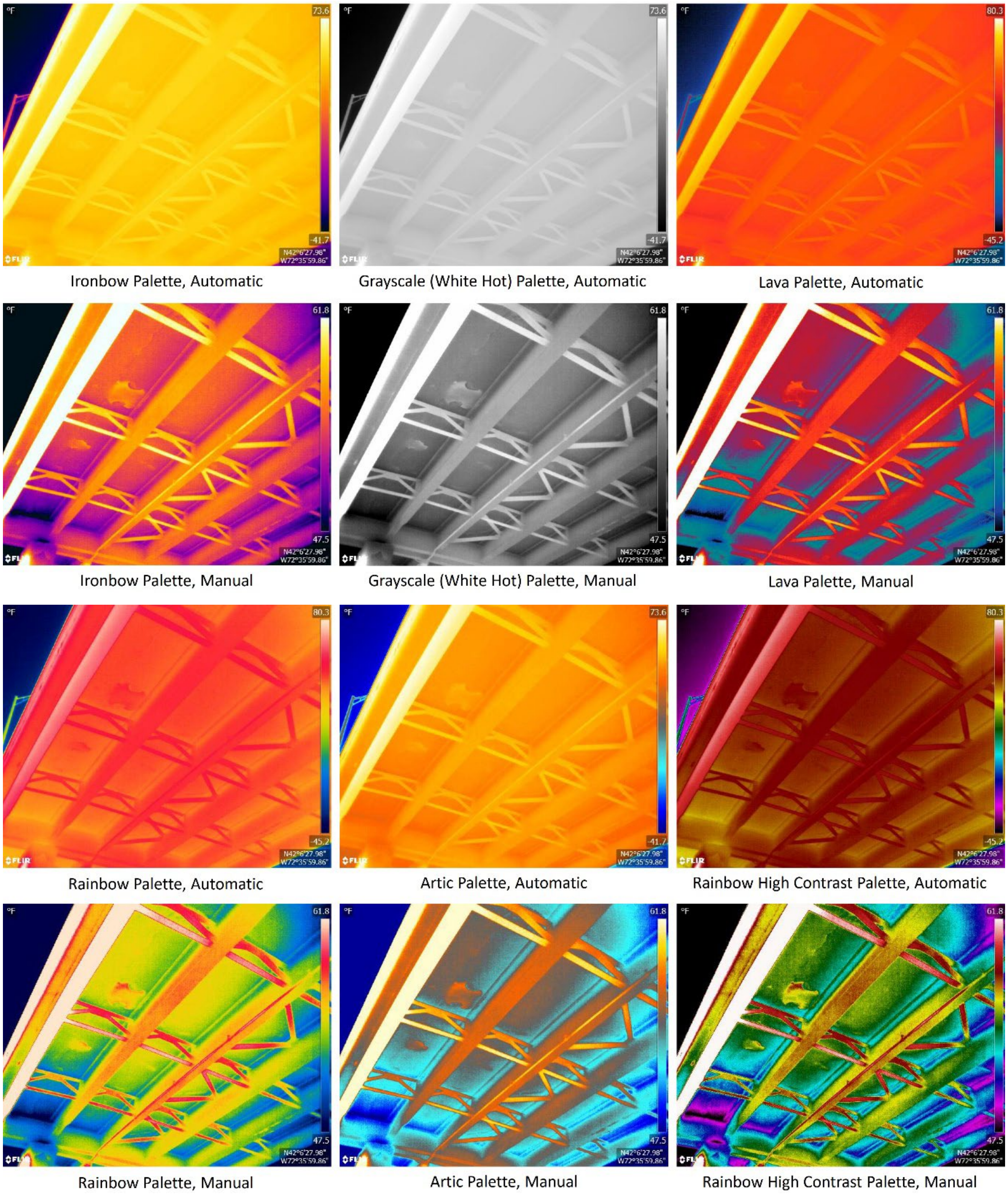


Figure 31 - Comparison of Color Palettes for Zenmuse XT2

3.3.3.2 - Thermal Analysis Software Packages

While it is preferable that thermal data be utilized under ideal field conditions with the field data being able to identify delaminations; sometimes this just isn't possible. Thermal analysis software can be used to view and edit radiometric imagery. Different manufacturers have different software available for this purpose. The recommended equipment, the Flir E96 and Zenmuse XT2, are both compatible with Flir Thermal Studio. Additional software includes DJI Thermal Analysis Tool (for Zenmuse H20T sensor which was not field-tested) and Fluke Connect (for Fluke thermal cameras), however, these software packages are not discussed as their relevant thermal cameras were either not recommended or not tested.

Flir Thermal Studio is available online and offers three plan options:

- Starter (free)
- Standard ($209 per year)
- Pro ($419 per year)

An overview of the Flir Thermal Studio plans is included in Appendix C. The Starter version will be adequate to perform edits of the thermal imagery for inspection purposes. The Starter version will allow the user to edit the color palette and temperature span, allowing optimization of the imagery for delamination detection (refer to Figure 32). An overview of the software package and basic processing steps are also provided in Appendix C.

Figure 32 - Thermal Studio Pro Screenshot

Adjusting the thermal span is a relatively simple operation in the software. There are two main ways to do so. The first way is to manually change the value in the minimum and maximum temperature boxes; these are located at the top and bottom of the temperature scale. The object parameter, geolocation, and metadata panel also includes two boxes for these values. The boxes that allow manual input of these values are indicated with blue arrows in Figure 33, on the following page.

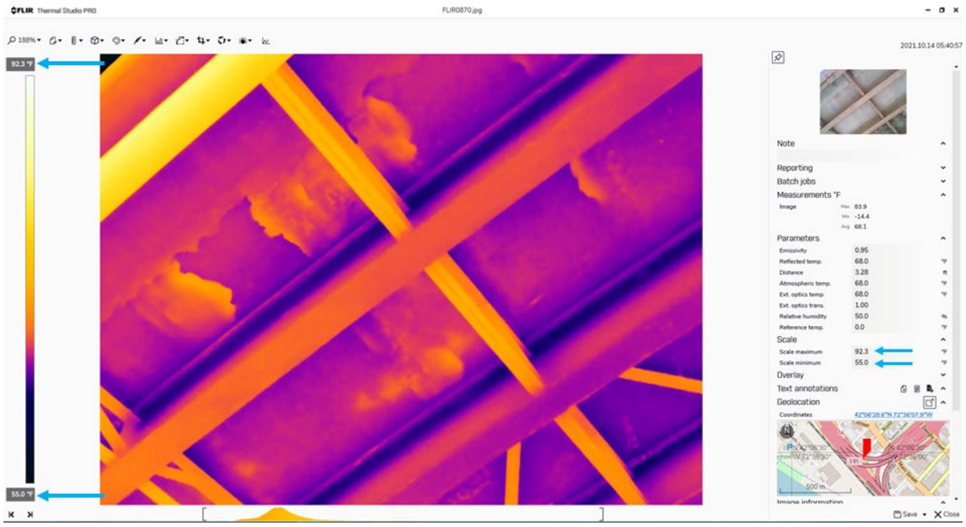


Figure 33 - Manual Entry for Minimum and Maximum Temperatures

The second way to adjust the temperature span is through the histogram located at the bottom of the screen and outlined with a black dashed box in Figure 34 below. The brackets ([ ] – indicated with green arrows in Figure 34) at either end of the histogram represent the minimum and maximum temperature values. If the user hovers the cursor over either bracket, the cursor will change to a horizontal line with arrows on either end. Once the cursor changes, the brackets can be clicked and dragged to adjust the minimum/maximum temperature values. If the user hovers the cursor over the histogram in between the brackets (indicated with the blue arrow), the cursor will change to a solid black circle with arrows on all four sides. Once the cursor changes, the histogram can be clicked and dragged to adjust the temperature span and level while leaving the existing temperature difference between minimum and maximum temperatures the same.

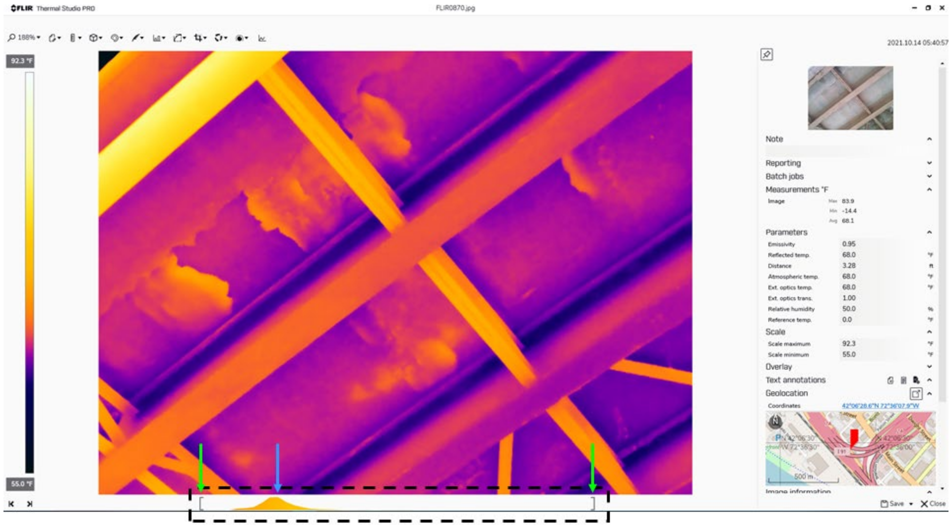


Figure 34 - Adjusting Temperature Values Using Histogram

3.3.4 - File Types

Flir thermal cameras use radiometric JPEG files, commonly notated as R_JPEG. The radiometric JPEG image file format was developed by Flir. Each pixel within the image will capture and store the temperature data from the thermal camera so that Flir thermal processing software will be able to analyze and edit thermal images. Additionally, the radiometric JPEG file is treated as a standard JPEG file by other software which allows users to view the gradient thermal image with most standard software packages and devices.

3.3.5 - Data Storage

Data storage considerations for thermal imaging should be relatively inconsequential. The specific data requirements will depend on the specific model of thermal camera being utilized but storage requirements should not be much larger than those needed for traditional NBIS inspection. A traditional 16 MP point and shoot camera will generate an approximately 3.5 – 4.0 megabyte (MB) file. When shooting R_JPEG and JPEG simultaneously, the files sizes for the recommended thermal cameras are anticipated to be approximately:

- Zenmuse XT2: 2 – 3 MB
- Flir E96: 0.60 – 1.00 MB

The data requirements for the use of drones in general will be a larger discussion based on the needs of the agency and method of implementation. Drones can be used to capture photographs or videos which can greatly vary in terms of storage space needed. Capturing video of an entire inspection will generate gigabytes (GB) of data; a single span bridge can be 10 GB of video. If drone imagery is used to develop a photogrammetric model or digital twin (discussed later in this report), even more storage space will be required.

3.4 - General Drone Protocols

There is a lot of potential variability in the use of drones for bridge inspection applications depending on the specific bridge and available equipment. Operational planning is a critical component in the implementation of drone technologies. A brief overview of planning steps is included for guidance. It is not intended to represent every possible situation, but rather, provide a starting point to build upon as drone implementation progresses.

3.4.1 - Airspace

Prior to performing any field work, the bridge site should be investigated to identify the airspace. The National Airspace System (NAS) is comprised of multiple layers of airspace with varying levels of restrictions. The airspace system can generally be subdivided into controlled (Classes A, B, C, D, E) and uncontrolled (Class G). Controlled airspace is primarily located around airports. In relation to drone operations, controlled airspace requires authorization from the FAA to perform flights and is generally limited to pre-approved ceilings, although additional permissions can be received to exceed these. Uncontrolled airspace does not require prior authorization but is limited to 400 feet above ground level (AGL).

Airspace authorizations can be received through the FAA Low Altitude Authorization and Notification Capability (LAANC) system or through the FAA Drone Zone web portal. LAANC will be used for airports that are on the LAANC system while FAA Drone Zone will be used for those that aren’t on the system. Typically, the airports that aren’t on the system are associated with the military. Multiple industry

LAANC service providers, such as Aloft, AirMap, and Drone Deploy, are capable of handling LAANC requests.

Airspace can be determined from Sectional Aeronautical Charts (see Figure 35), online databases such as the FAA UAS Data ArcGIS map (see Figures 36 and 37), or LAANC service providers. The FAA UAS Data ArcGIS map and LAANC service providers include only the approved ceiling for UAS operations and not the full area of controlled airspace. The approved ceilings colored green indicate that the airport is on the LAANC system and ceilings colored red indicate that the airport is not on the LAANC system. LAANC requests for altitudes beneath the approved ceilings will generally receive instantaneous approval. Requests exceeding the approved ceilings will need to be reviewed by Air Traffic Control (ATC) and can take up to 90 days to approve. However, the duration will be dependent on the specific airport. In AECOM's experience with Boston Logan International Airport, these requests have been reviewed and approved in less than a week.

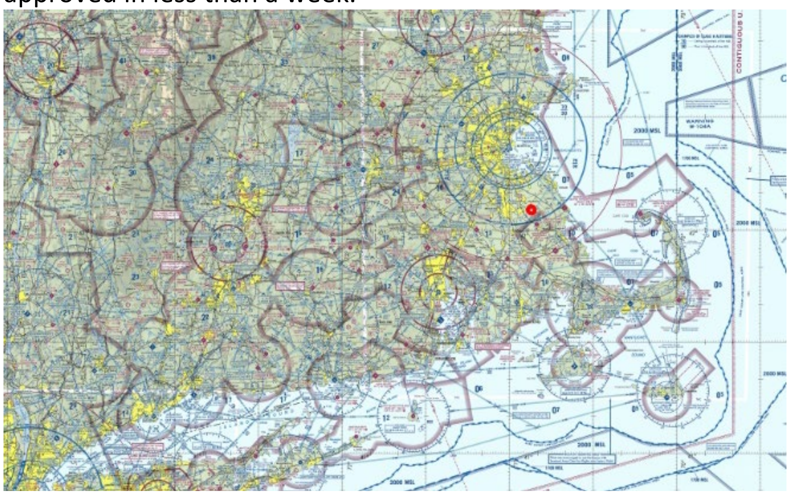


Figure 35 - Sectional Chart of CT, MA, RI

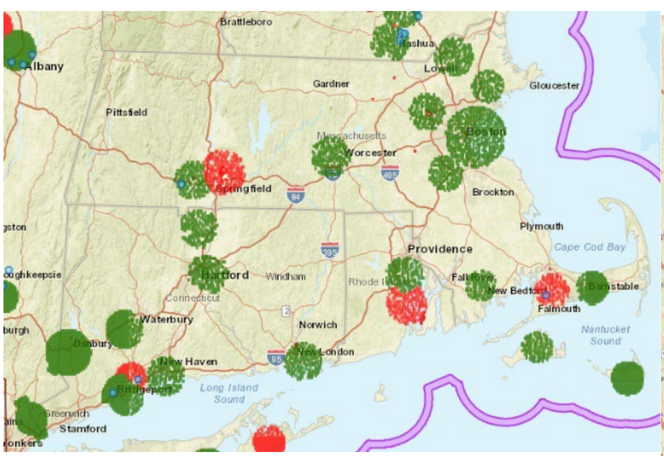


Figure 36 - FAA ArcGIS Map of CT, MA, RI

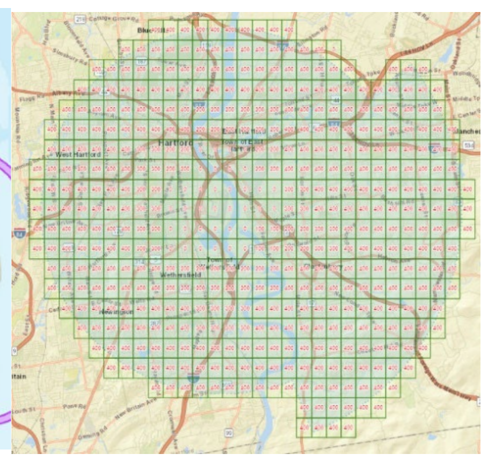


Figure 37 - ArcGIS Map of Brainard Airport in CT

If a DJI drone is being utilized, it is recommended that the DJI Geo Zone map be checked for any additional restricted zones instituted by the manufacturer that may impact operations (refer to Figures

38 and 39, on the following page). The DJI Geo Zone map can be found here: https://www.dji.com/flysafe/geo-map. The DJI Geo Zones include:

- "Restricted Zones" are indicated by red outlines and shading. These are primarily limited to areas directly adjacent to airports and/or sites with security concerns, such as prisons or military facilities. Restricted Zones need to be unlocked through a DJI Unlocking request which will require a copy of the FAA airspace authorization and/or waivers to be submitted.
- "Altitude Zones" are indicated by gray outlines and shading. These are limited to the approaches of runways. These zones institute altitude limits. For bridge inspection, these altitude limits will likely not impact operations.
- "Authorization Zones" are indicated by blue outlines and shading. These are located around airports. These zones can be self-unlocked by authorized users with a DJI verified account.

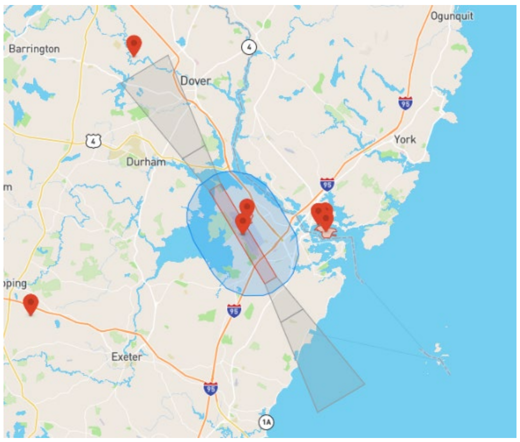


Figure 38 - DJI GeoZone Map of Pease International

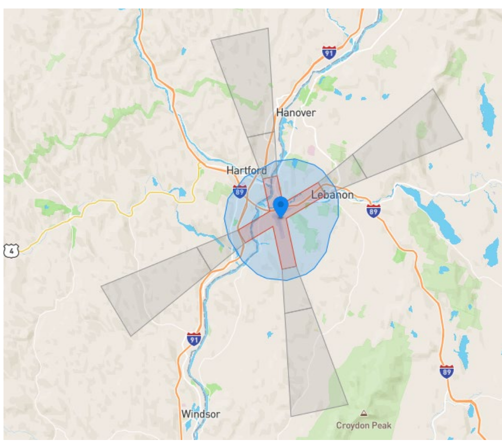


Figure 39 - DJI GeoZone Map of Lebanon Municipal Airport

3.4.2 - Planning

Operation planning is an important step to ensure safety and successful completion of operations. During the planning phase, UAS staff should:

- Perform planning for typical inspection activities including updating emergency contact and nearby hospital locations. Provide notification of activities to agency staff as required.
- Identify whether the bridge has a beneficial application for drones and identify the required equipment based on the anticipated use case.

- Determine the required flight crew and schedule properly trained and qualified staff. Potential roles include Remote Pilot in Command (RPIC), VO, Sensor operator (SO), and bridge inspector based on use case. For an operation being performed to support an NBIS bridge inspection, at least one member of the flight crew shall be an NBIS qualified team leader.
- Determine whether FAA airspace authorizations or waivers are required. Airspace authorization requests will be submitted through LAANC or the Drone Zone web portal. Waiver requests will be submitted through the FAA drone zone portal.
- Check for special use airspace, such as restricted zones, military operation areas (MOAs), alert areas, etc. that may restrict or otherwise affect the operation.
- Determine property ownership and retrieve permissions from property owners in accordance with agency policy.
- Check for local airports in uncontrolled airspace. Depending on proximity to the bridge, the UAS pilot should consider notifying the local airport manager.
- Review the bridge site in Google Maps, Google Earth, or equivalent program to identify site obstacles, obstructions, terrain, potential wildlife, and the potential for non-participant access to the site. Identify potential launch/recovery positions. Identify potential VO locations.
- Determine anticipated flight duration and required batteries. If not enough batteries are available, obtain power inverter for vehicle or generator to charge batteries during the operation.
- Prior to mobilizing for the inspection, make sure that the drone and controller firmware is current and that the batteries and controllers are fully charged.

3.4.3 - Hazards and Risk Assessment

It is important that the drone pilot identify potential hazards related to drones and perform a risk assessment prior to performing field work. Common hazards related to bridge inspection include:

- High winds, especially for tall bridges crossing rivers.
- Turbulent winds, which can be unpredictable adjacent to the bridge superstructure and substructure. In some cases, swirling winds can cause turbulence that can pull a drone towards the bridge structure.
- EMI due to the bridge steel, which can disrupt internal measurement unit (IMU) and compass calibration.
- Power lines running along the side of the bridge, which could cause EMI or provide a drone collision hazard.
- Potential for limited visual line of sight, which may necessitate performed drone operations from a boat beneath the bridge.
- Eagles and hawks, which are more likely to be present along rivers, have been known to perceive drones as a threat and attack drones.
- Return-to-Home functionality could cause a drone to fly up into the underside of a bridge deck as many return-to-home systems do not allow the return-to-home elevation to be set below 60 feet.
- Drivers that can be distracted by drones flying within their sight lines.

Risk assessments should be performed for every operation in accordance the agency’s UAS policies and procedures.

3.4.4 - Site Deployment and Flight Operations

Site deployment and flight operations also require the same level of care and detail as the planning phases. Once on site, UAS staff should:

- Hold a safety toolbox meeting to review safety items, the overall inspection, and the anticipated drone operation with the inspection team. This includes the launch/recovery locations for the drone, potential VO locations, the anticipated flight path, and an overview of emergency procedures. Review nomenclature and terminology with flight crew to ensure consistency throughout the operation.
- Perform an on-foot site walk to verify that site conditions match expected and identify any unforeseen or changed hazards. Revise task hazard assessments, hazard mitigation, and risk assessments as necessary.
- Set up a launch position that is protected from pedestrians and vehicles.
- Inspect the condition of the UAS, sensors, controller(s), and batteries to ensure they are in satisfactory condition. Check for damage such as gouges, stress fractures, swelling of batteries, etc. Verify that drone firmware and control software are up to date.
- Set up the drone and required sensors. If a thermal camera is being used, position the drone so that the thermal camera is not pointed towards the sun to avoid sensor damage.
- Perform all pre-flight checks, review of weather conditions including wind speed, gust speed, visibility, and cloud cover, and check again for temporary flight restrictions (TFR's) and notice to airmen (NOTAMs).

The flight operations should include:

- Pre-flight check to verify the GPS signal, UAS telemetry, battery life, and control signal.
- Start the drone motor and hover approximately 10' to 15' above the launch site to check the controls (perform at least one movement with each control to verify proper functionality). The UAS pilot should also watch and listen for any abnormalities.
- Perform UAS operations for data collection which can be performed manually or with automated flight software.
- Flight crew shall monitor the weather for changing conditions such as wind speed and precipitation. Be prepared to cease operations, either temporarily or for the day, if weather conditions become unsafe.
- Review and download imagery from memory card after every flight. Check imagery for gaps in data, proper focus, proper exposure, and any blurriness. If needed, re-fly locations with unusable data.

3.4.5 - Drone Inspection Applications

Beyond the use of thermal imaging, drones have the potential to be a valuable tool for visual imagery as well. The most recent version of the National Bridge Inspection Standards, published on 5/6/2022, includes discussion on UAS and other advanced technologies for bridge inspection. The Federal Highway Administration (FHWA) acknowledges that these technologies have the potential to improve efficiency and increase safety but indicates that they may not supplant traditional inspection personnel and methods. The FHWA states that the use of UAS should primarily be used as a supplement and not compromise the thoroughness and effectiveness of a bridge inspection [1]. Drones are best suited to serve as another "tool in the toolbox" for bridge inspectors to use in the right situation based on engineering judgement. The bridge inspection team leader should be on-site and viewing the drone visual feed during any UAS bridge inspection operations.

Specific UAS applications for bridge inspection depend on numerous factors including, but not limited to the following:

- Bridge structure type and material

- Bridge condition
- Age of bridge
- Type of roadway carried
- Site features beneath the bridge
- Type of inspection
- Level of detail required
- FAA airspace restrictions
- Available drone system

It is recommended that the use of UAS for bridge inspection be an open discussion between the state agencies and their respective FHWA division representatives. Since every bridge is different in terms of condition, structure type, and access, communication can help facilitate acceptance of UAS inspection applications as well as proactively address potential concerns.

While the scope of this research project did not include investigating applications for general drone inspection, AECOM has developed potential applications based on previous experiences with UAS technologies for different clients. There is no one size fit all drone solution. Each drone has its own sets of strengths and weaknesses where different drones may be better suited to different applications.

3.4.5.1 - Inventory / Record Photos

Inventory photos, such as bridge approaches, elevations, general underside, general topside, and upstream/downstream views, are required to be documented as part of inspections at different intervals. Drones provide a tool to assist with this process.

The use of drones potentially increases safety for inspection staff by avoiding loose terrain around embankments, climbing over railings/fences, and avoiding walking through brush and vegetation. Poison ivy is a very common hazard for bridge inspectors which can be avoided through the use of a drone. The drone can also provide improved image quality and context providing better insight into the adjacent areas for inspection planning. Figures 40 through 42 (shown below and on the following page) show several examples of traditional inventory photos versus a drone image.

Figure 40 - Terrestrial versus Aerial Elevation of Girder Bridge


Figure 41 - Terrestrial versus Aerial Elevation of Steel Box Girder Bridge


Figure 42 - Terrestrial versus Aerial Elevation of Truss Bridge

3.4.5.2 - Aerial Imagery

Aerial imagery can provide a new perspective for inspectors to document bridge deterioration. This aerial view can help put the overall condition of the bridge into a more "big picture" perspective. Typically, the report text and photos will focus on the most deteriorated locations, which can skew the perspective of the overall condition. Aerial views can help reduce this perception.

These types of images can also provide clear detail of defects to truly understand the deterioration. Each inspector can have different interpretations and ways of documenting such that the same defect can be described in multiple ways. An aerial image can help provide a clear record of the deterioration. While imagery can also be taken on the ground, the lower angle does not always provide enough context. Some detail will be lost in drone images based on the distance, so both terrestrial and aerial images should be used to adequately show the condition (refer to Figures 43 and 44, shown below and on the following page).

Figure 43 - Terrestrial versus Aerial Image of Wearing Surface

Figure 44 - Terrestrial versus Aerial Image of Wearing Surface

3.4.5.3 - Visual Screening Tool

Drones can function as an initial screening tool for inspections. Typical inspection access requires the use of access equipment (typically under-bridge inspection vehicle, aerial lift, or bucket truck), temporary traffic control including cones or barrels and truck-mounted attenuator, and police detail(s). Depending on the specific equipment and vendor, these costs can equal over $6,000 per day. The use of drones may reduce the amount of time needed for access equipment. This saves the direct costs for the equipment as well as reduces the amount of time for traffic closures which can negatively impact the traveling public.

The drone can perform a visual pass of the bridge to identify locations requiring a better look or hands-on access by bridge inspectors. This type of application is similar to inspectors “sweeping” the underside of a bridge span while inside the bucket of an under-bridge inspection vehicle. As mentioned previously, the team leader needs to be viewing this footage and providing direction for locations and viewing angles to focus on. The intent is not to eliminate but reduce the time needed for hands-on access. The reduction is going to be heavily dependent on the condition of the bridge. Drones can only provide a visual image, so any element that requires a physical (tactile) technique, such as hammer sounding, chipping delaminated concrete, or cleaning rust from steel surfaces for evaluation of the condition will require hands-on access.

Several inspection applications where the drone can be used to identify whether hands-on access is required include:

- Underside of bridge decks (refer to Figures 45 and 46, both on Page 47)
- Girders and floorbeams (refer to Figure 46 on Page 47)
- Arches, slabs, and rigid frames (refer to Figures 47 and 48, both on Page 47)
- Exterior faces of truss members or secondary truss bracing (refer to Figure 49 on Page 47)
- Bridge members extending above the bridge deck, such as decorative pylons, towers, secondary support trusses, ancillary structures (refer to Figures 50, Page 47 and 51, Page 48)
- Cable stays (refer to Figure 52 on Page 48)
- Roof and sidewalls of covered bridges (refer to Figure 53 on Page 48)
- Tall piers

Figure 45 - Underside of Deck Overhang and Girder Web

Figure 46 - Underside of Deck

Figure 47 - Underside of Concrete Arch


Figure 48 - Underside of Concrete Slab

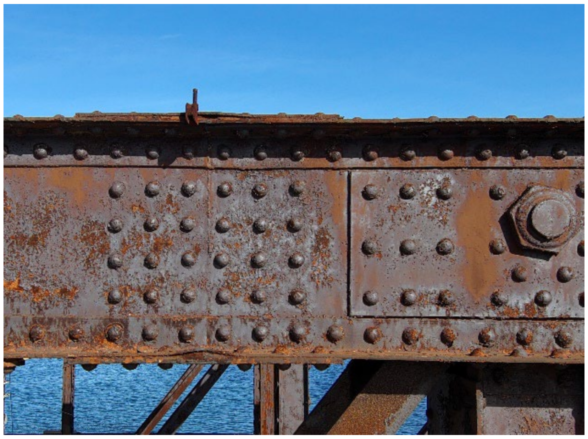


Figure 49 - Truss Upper Chord


Figure 50 - Counterweight Truss

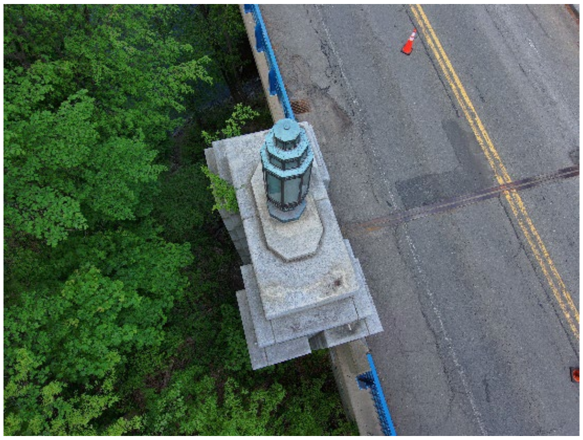


Figure 51 - Top of Pylon


Figure 52 - Helical Bead Damage to Cable Stay


Figure 53 - Roof of Covered Bridge

3.4.5.4 - Channel Inspection

Inspections over waterways require observations on the channel itself to monitor potential movement and scour. Drones provide a quick way to review the channel upstream and downstream of the bridge to review the condition of the channel. Drones can visually identify embankment erosions, aggradation, debris, and vegetation affecting the channel flow as well as deterioration of channel/retaining walls (refer to Figures 54 and 55). This prevents the inspector from needing to climb down an embankment or walk-through brush and trees reducing the risk of trips, ticks, and poison ivy.

Figure 54 - Aggradation with Vegetation Growth along Channel Upstream of Bridge

Figure 55 - Channel Wall Deterioration Downstream of Bridge

3.4.6 - Drone Limitations

While drones offer a new tool for inspections, there are several limitations to these technologies. Some of these limitations will be related to the capabilities of the individual drone while others will be related to specific bridge sites or inspection regulations.

Drones can only provide a visual image that is limited in detail by the sensor. Drone sensors can range in resolution from 12 MP to 48 MP depending on the specific drone. However, the proximity of the drone to the subject also plays a factor. A 12 MP image taken at 5 feet will provide more detail than a 24 MP image taken at 15 feet. This concept, ground sampling distance (GSD), is important for understanding imagery quality. Ground sampling distance is the distance between two consecutive pixel centers which essentially means that the GSD is the linear width/height of each pixel. A larger GSD value would mean that each pixel is capturing a larger area and thus less detailed would be captured. Smaller GSD values can be achieved by flying closer to the subject or using a camera with a higher megapixel sensor.

Lighting conditions with large contrast affect image exposure. Dynamic range is the range from brightest to darkest visible area of an image. The human eye can see brighter and darker areas than image sensors. The extent of deficiencies can be lost in shadows caused by the more limited dynamic range of a sensor (refer to Figures 56 and 57). The UAS pilot will need to account for the limitations in dynamic range either through modifying the drone flight path, adjusting the exposure compensation in automatic camera mode, or establishing manual camera settings during the flight. Wider bridges may have reduced lighting underneath the center of the bridge, which may limit the usefulness of the drone visual imagery.

Figure 56 - Different Exposure Compensation Settings

Figure 57 - Inadequate Visual Imagery due to Bridge Geometry and Lighting

Bridge geometry can also be a limitation, depending on the specific drone system being utilized. Most drones operate based on GPS signal for flight stability which can be lost when flying under bridges. This creates a higher risk environment for the drone, especially when flying between girders or truss members. Additionally, the geometry can make it difficult to view portions of the bridge. Some examples of this include:

- Spacing between multi-girders limiting the view of the bottom of the web and top face of bottom flange (refer to Figure 58)
- Joints/gaps between adjacent box beam sections (refer to Figure 59)
- Lateral or cross bracing limiting access to stringers, floorbeams, or girders (refer to Figure 60)
- Built-up truss members and gusset plates (refer to Figure 57 on Page 49)

- Bearings that leave minimal height between the superstructure and substructure (refer to Figure 61)

Figure 58 - Limited View of Bottom of Girder Web and Top of Bottom Flange

Figure 59 - Limited View of Vertical Face at Gap between Box Sections

Figure 60 - Lateral Bracing Limiting View of Stringers

Figure 61 - Limited View of Bearing and Top Pier

An additional consideration for drone usage is the ability of the inspector to effectively view the screen. Sun glare can obscure the imagery when viewed in the field which can negatively impact an inspection through missing deterioration or capturing out of focus photos (refer to Figure 62). There are commercial products available in the form of glare resistance screen protectors and sunshades; however, this will vary on the specific drone model and controller (refer to Figure 63). If neither of these products are available, the inspector should try to position themselves in a shaded area. The use of a portable canopy may be beneficial for field operations to provide shade. The imagery should be reviewed on a laptop in the field prior to completing field activities and demobilizing.

Figure 62 - Screen Glare on Skydio Enterprise Controller

Figure 63 - Sunshield on DJI Crystal Sky Tablet

As previously mentioned, drones are only able to capture visual imagery and are unable to perform physical activities such as cleaning steel, chipping loose concrete, or sounding concrete to identify delaminations. The inspector needs to understand these limitations and make sure the drone is used only when it is the appropriate tool.

4 - Implementation Plan

This research project is only the first step in implementing thermal imaging and drone technologies into bridge inspections. The research project provides guidance for state transportation agencies to understand the basic principles and best use cases for these technologies.

4.1 - Recommended Equipment

This research project included field-testing of multiple handheld and drone-mounted thermal cameras. Based on the field-testing and data analysis, the use of a handheld Flir E96 or Zenmuse XT2 mounted to either a DJI Matrice 210 or 300 provide the best likelihood for the detection of concrete delamination. Product specifications for the Flir E96 and Zenmuse XT2 are included in Appendix D.

However, during the research project, the Zenmuse XT2 was discontinued. The replacement model, the Zenmuse H20T, while not field-tested, is expected to perform similarly to the XT2. While the protocols for implementation will have slightly different steps for this camera, the overall recommendations and procedures will be the same. The product specifications for the Zenmuse H20T are also included in Appendix D.

4.2 - Training Considerations

The implementation of thermal imaging and drones for bridge inspection requires additional trainings for bridge inspection staff in order to ensure consistent analysis of thermal data and safe implementation. The scope of work for this research project did not include development of training but rather a discussion of considerations for these trainings.

4.2.1 - Thermal Imaging

Bridge inspectors that will be utilizing thermal cameras during inspections should receive training in the operation of the camera as well as data analysis. The analysis of thermal imagery should include an introduction and overview of thermal analysis software. AECOM recommends two days of training that includes the following topics:

- Thermography basics
- Analysis of thermal imagery focused on concrete delamination
- Flir E96 training
- Flir Thermal Studio training

There are existing thermography training courses that are available that extend longer than two days. However, these training courses are generally geared towards the power industry and focused on applications for electrical transmission line inspections and solar panel inspections. A focused training effort on concrete delamination should be able to be successfully completed in two days. The training can include a blend of virtual and in-person training.

4.2.2 - Drone

AECOM recommends each agency provide UAS training consisting of both classroom and field training for any UAS staff. While this training can be provided by in-house staff, consultant, or other vendor, it is important to ensure that UAS pilots have adequate training for their anticipated flight operations. Training staff should be familiar with UAS structural inspection including bridges.

While the specific training will vary based on the anticipated drone applications and pilot background, it is critical that practical field training is included since the FAA Part 107 Knowledge Exam does not include any field-test. AECOM recommends a five-day training program that includes the following topics:

- Overview of Agency Policies
    - UAS
    - Media/News Agencies
    - Privacy
- FAA Documentation
    - Registering drone
    - Incident reporting
- Flight Planning
    - FAA authorizations and waivers through the FAA LAANC and Drone Zone portal
    - DJI Geofencing and unlocking requests
    - Useful applications for mission planning (iFlight Planner, FAA B4U Fly, FAA UAS Data ArcGIS map, Sky Vector, Google Earth, etc.)
    - Weather considerations
    - Site scoping
    - Site deployment (launch/recovery locations, VO locations, etc.)
    - Automated flight apps (DJI Ground Station Pro, DJI Pilot, Drone Deploy, Pix4D, Universal Ground Control Station, Litchi, Drone Harmony, etc.)
- Site Deployment
    - Site walkthrough
    - Field safety / toolbox meeting
    - Equipment checks / Pre-flight and flight checklists
    - Weather monitoring
- Drone Overview
    - Maintenance
    - Record keeping
- Safety
    - Potential hazards
    - Risk assessment
    - Types of flight emergencies
    - Emergency procedures
- Flight Skills (field training)
    - Basic flight
    - Aerial mapping and photogrammetry
    - Flights near and under bridges
    - Emergency procedures
        - “Atti” mode for loss of GPS signal
        - Auto-return to home procedures
        - Flights with loss of control screen
        - Incoming manned aircraft
        - Eagle/hawk encounters
        - Inclement weather

4.3 - Cost Estimate for Implementation

Cost estimates were developed as part of the Task 3 Interim Report based on the recommended equipment and anticipated training requirements. These costs represent the initial upfront costs for incorporating these technologies. The overall costs are summarized in Table 12 and are further discussed below.

Table 12 - Cost Estimate Summary Table

Cost Estimate Summary Table	
Item	**Subtotal Cost**
Thermal Training Costs	$ 5,120.00
Thermal Equipment Costs	$ 13,700.00
Drone Training Costs	$ 13,675.00
Drone Equipment Costs	$ 32,447.00
Total Cost	**$ 64,942.00**

4.3.1 - Training Costs

The training costs included in this section are based on the discussion in Section 4.2 - Training Considerations on Page 52. The training programs are anticipated to include 5 staff members from the agency for a duration of two days for thermography training and five days for drone training (refer to Tables 13 and 14, Page 55). It is assumed that the training will be performed with a mid-level engineer with between 5 to 10 years of experience. A raw direct hourly rate of $38 per hour was utilized. The trainer is anticipated to be performed by a vendor at a rate of $50 per hour with a 2.6 multiplier to account for overhead and profit.

Staff that are receiving drone training will also need to obtain an FAA Part 107 Commercial UAS license. No labor costs are included for this process; however, the test fee is included within the estimate.

The costs to develop a training program have not been included since the training provider could vary between in-house agency staff, a consultant, or a vendor.

Table 13 - Thermal Training Costs

Thermal Training Costs					
Item	**Days**	**# Staff**	**Unit Cost***	**Unit**	**Subcost**
Agency Staff - Training Time	2	5	$ 38.00	$/Hr	$ 3,040.00
Trainer Time	2	1	$ 50.00	$/Hr	$ 2,080.00
				Subtotal	**$ 5,120.00**

** Unit cost represents the raw direct hourly rate for staff labor hours. For agency staff, no multiplier is applied. For trainer staff, a 2.6 multiplier is applied.*

Table 14 - Drone Training Costs

Drone Training Costs					
Item	**Days**	**# Staff**	**Unit Cost***	**Unit**	**Subcost**
Agency Staff - Training Time	5	5	$ 38.00	$/Hr	$ 7,600.00
Agency Staff - Part 107 Test Fee	-	5	$ 175.00	$/Test	$ 875.00
Trainer Time	5	1	$ 50.00	$/Hr	$ 5,200.00
				Subtotal	**$ 13,675.00**

** Unit cost represents the raw direct hourly rate for staff labor hours. For agency staff, no multiplier is applied. For trainer staff, a 2.6 multiplier is applied.*

4.3.2 - Equipment Costs

The equipment costs for the recommended handheld thermal camera, the Flir E-96, include purchasing all three available lenses (12°, 24°, and 48°) in order to provide the greatest flexibility for data capture. This cost is included in Table 15.

Table 15 - Handheld Thermal Equipment Costs

Thermal Equipment Costs			
Item	**Unit**	**Unit Price**	**Cost**
Flir E-96 (with 12°, 24°, and 48° Lenses)	1	$ 13,700.00	$ 13,700.00
		Subtotal	**$ 13,700.00**

The recommended field-test drone-mounted thermal camera was the Zenmuse XT2. However, the camera has since been discontinued. The replacement model, the Zenmuse H20T, is expected to perform similarly to the XT2. While the protocols for implementation will have slightly different steps for this thermal camera, the overall recommendations will be the same.

The Zenmuse H20T is paired with the DJI Matrice 300. The cost for this equipment and related accessories is included in Table 16, on the following page.

Table 16 – Drone-Mounted Thermal Camera Equipment Costs

Drone Equipment Costs			
Item	**Unit**	**Unit Price**	**Cost**
DJI Matrice 300	1	$ 13,700.00	$ 13,700.00
Zenmuse H20T Thermal Camera	1	$ 11,800.00	$ 11,800.00
M300 Hardcase (HPRC2800W)	1	$ 887.00	$ 887.00
TB60 Batteries	6	$ 700.00	$ 4,200.00
M300 Prop Set	2	$ 120.00	$ 240.00
M300 Controller	1	$ 1,375.00	$ 1,375.00
WB37 Batteries	4	$ 60.00	$ 240.00
FAA Registration	1	$ 5.00	$ 5.00
		Subtotal	**$ 32,447.00**

The Matrice 300 comes with two TB60 batteries (one set) which allow for one flight before needing to recharge. While the advertised battery life for the Matrice 300 is 55 minutes; that is for ideal conditions and no sensor payload. With a Zenmuse H20T, the flight time is estimated as 43 minutes. Accounting for proper flight standards, which would include landing a drone with battery at 20%, the flight time will likely be approximately 30 minutes. The cost estimate includes an extra six TB60 batteries (three sets) in addition to the batteries included with the drone purchase to allow for longer flight duration and approximately 2 hours of flights. Flight time beyond this will require the purchase of additional batteries or the use of a generator to charge batteries in the field.

The drone cost estimate also includes the purchase of an additional controller so that the drone can be flown in a master/assistant set up. The estimate also includes four extra WB37 batteries for the controllers.

4.4 - Potential Impediments to Implementation

There are several potential impediments to implementation of these technologies. The largest impediment would be the cost of equipment and staff training requirements. The research team estimates approximately $65,000 for full implementation. However, partial implementation (i.e. focusing on solely thermal or drone implementation), may serve as a potential way to move forward with implementation if costs are prohibitive.

The length of time to develop an appropriate training program may also be a potential impediment. Multiple departments, including Aeronautics/Aviation, Bridge, and Nondestructive Evaluation, may need to provide input to ensure compliance with existing policies. These reviews may lead to internal discussions to resolve issues or concerns with the proposed training. The length of time to complete this process could delay implementation of the technologies.

Drone implementation will require the development of a programmatic system for oversight to ensure quality and safety. A programmatic approach is needed to ensure safe drone operations. Standardized operational processes, such as pre-flight checklists and risk assessments help to mitigate risk and ensure safe completion of drone flights. If a drone program has not already been established, the development of said program would require time, potential hiring of resources, and additional cost.

4.5 - Activities Necessary for Implementation

The use of thermal imaging and drone technologies can be beneficial as part of the bridge inspection process. Thermal imaging will take some time for the user(s) to gain familiarity with the technology and the temperature change requirements. While it may be tempting to return to the existing traditional methods after only a few tries, agency staff should persevere through the initial difficulties with these new technologies.

However, it is important to understand the limitations of the technology, especially when it is being used to inspect above a portion of a bridge deck above a roadway carrying the traveling public. There is no guarantee that a thermal camera will identify delaminations and the thermal image will not be able to portray whether the location is a hollow sounding area or an incipient spall. The guidelines included in this report will assist in implementing the technologies within the limits of their capabilities.

AECOM recommends the following steps for the New England state transportation agencies:

- Develop guidance documents for identifying specific bridges to implement these technologies for in-house inspection staff and consultants. The guidance can be in the form of a policy memo or content as part of a bridge inspection manual.
- Develop drone pre-qualification or certification programs for consultants to ensure safe operation of drones. Each agency should include a review of the consultant's overall drone program focusing on programmatic safety requirements, insurance, pilot qualifications, and workflow to ensure safety and quality.
- Conduct training on thermal imaging and drone technologies for in-house staff.
- Continue to monitor new technologies and research projects for potential implementation. Drone technology is rapidly evolving and may lead to new applications for inspection.
- Perform pilot projects to continue to collect data related to thermal imaging for concrete delamination in order to refine protocols and improve recommendations related to weather and temperature conditions.
- Consider funding research for 3d photogrammetric modeling and machine learning for defect analysis. Discussion on both of these topics is included in the Task 3 Interim Report, beginning on Page 40.

5 - Workshops

Near the end of this research project, it was determined that there would be remaining funds. Discussions with the Technical Committee lead to the decision to utilize the remaining funds to provide workshops to serve as introductory training and provide demonstrations to IRTI and UAV technologies to transportation agency staff. The introductory training included a two-hour virtual presentation and a four-hour in-person session.

The virtual training session was held on Friday, May 12th using Microsoft Teams. The presentation slides are included as Appendix E. The virtual training session consisted of the following topics:

- Background
- Thermal Imaging
    - Terms and Definitions
    - Applications
    - Data Capture and Analysis
- UAV (Drones)
    - Drone Basics
    - Limitations and Considerations
    - Drone Applications
    - Introduction to Photogrammetric Modeling

The in-person workshop sessions were held between Wednesday, May 24th and Friday, June 2nd with AECOM staff traveling to different bridge sites in each state. The intent of the workshops was to provide hands-on time with different pieces of equipment in order to help provide an understanding of the capabilities and limitations of each. The workshops consisted of the following topics:

- Introduction
- Thermal Imaging
    - Review of Terminology / Concepts
    - Participants using Thermal Cameras
    - Overview of Data Collection Procedures
- Drones
    - Safety
    - Deployment / Operational Planning
    - Inspection Applications
    - Demonstration of Drones
    - Participants Fly Skydio S2 (under close supervision)
    - Participants serve as Sensor Operator on DJI Matrice 210/300

6 - Conclusion

Thermal imaging and drone technologies serve as an additional tool for bridge inspectors. While these technologies offer benefits for efficiency and safety, they should not be considered a latch key solution to be implemented at every bridge. Engineering judgement should be used to implement the technologies in situations that are effective and efficient while maintaining or exceeding existing standards for quality.

Thermal imaging is able to detect varying degrees of concrete delamination along the underside of bridges under the right conditions. Based on the field-testing performed as part of this research project, the Flir E96 and Zenmuse XT2 thermal sensors provided the best results for detection of concrete delamination along the underside of bridges. Based on the limited data collected which was field verified based on manual hammer sounding, a minimum of a 10° Fahrenheit (for handheld) or 15° Fahrenheit (for drone-mounted) temperature swing over a 6-hour period is recommended for adequate detection capabilities. Even under ideal conditions, it is possible that not all delaminations will be detected by thermal imaging. Delaminations that are minor, small in size, or deeper within the deck may not be detected. However, for the bridges that were used for field-testing of the drone-mounted thermal cameras (BINs 114 and 4RT), more areas of delamination were identified than were noted as part of the previous routine bridge inspection report.

Drones can be utilized to capture inventory/record photos, general aerial imagery, as a visual screening tool, and channel inspections. Drone technology continues to rapidly evolve. The New England state transportation agencies should continue to follow the state of the practice as new applications and use cases are investigated. While bridge inspections have historically been a challenging application due to the need to have upward facing sensors, potential for loss of GPS connectivity, EMI, and obstructions preventing visual line of sight, drone technology will continue to improve and reduce the impact of these factors.

The transportation agencies should continue to monitor new technologies and applications in order to identify the most efficient and valuable methods of implementation. Future research and pilot programs should be considered in order to help provide further guidance on these technologies. While initial implementation won't be a guaranteed success as unfamiliarity with the equipment and methodology will provide a barrier, the long-term implementation has many potential benefits for improving efficiency, enhancing data quality, and increasing safety.

7 - References

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[4] ASTM D4788-03: Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography, ASTM International, 1988

[5] 14 CFR Part 107 – Operation and Certification of Small Unmanned Aircraft Systems, Federal Aviation Administration (FAA) and Office of the Secretary of Transportation (OST), Department of Transportation (DOT), 8/29/2016 https://www.federalregister.gov/documents/2016/06/28/2016-15079/operation-and-certification-of-small-unmanned-aircraft-systems