AECOM

New England Transportation Consortium (NETC)

NETC 20-3

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

Task 3 Interim Report

Inspection and Analysis Protocols

7/15/2022

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The following are the members of the Technical Committee that developed the scope of work for this research project and provided technical oversight throughout the course of the research:

- John "Sam" Maxim, Maine Department of Transportation (Technical Committee Chair)
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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 third task of this research project includes the development of inspection and analysis protocols for thermal imaging to identify concrete delamination along the underside of bridge decks. The protocols are based on the field testing performed as part of Task 2.</td></tr>
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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

AASHTO = American Association of State Highway and Transportation Officials
ASTM = American Society for Testing and Materials
BIN = Bridge Identification Number
CEI = Construction Engineering and Inspection
CS = Condition State
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
IMU = Internal Measurement Unit
IR = Infrared
LAANC = Low Altitude Authorization and Notification Capability
MB = Megabyte
mm = millimeter
MOA = Military Operations Area
MP = Megapixels
mph = Miles per hour
MSX – Multi-Spectral Dynamic Imaging
n/a = Not applicable
NAS = National Airspace System
NBE = National Bridge Element
NBIS = National Bridge Inspection Standards
NETC = New England Transportation Consortium
NDE = Non-destructive Evaluation
NOTAM = Notice to Airmen
OBIA = Object Based Image Analysis
PIP = Picture-in-Picture
RGB = Red, Green, Blue
ROW = Right of Way
SO = Sensor Operator
Temp = Temperature
TFR = Temporary Flight Restriction
UBIU = Under bridge inspection unit, commonly referred to as a snooper truck
UAV = Unmanned Aerial Vehicle
UAS = Unmanned Aircraft System
VO = Visual Observer

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Introduction

This report was developed as part of New England Transportation Consortium (NETC) research project 20-3 Investigating Thermal Imaging Technologies and Unmanned Aerial Vehicles (UAV) to Improve Bridge Inspections. The terms UAV, unmanned aircraft system (UAS), and drone are frequently used interchangeably. 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.

Task 3 for this research project includes developing the inspection and analysis protocols for the implementation of these technologies as well as addressing data storage, software, and training considerations. The protocols and guidelines discussed within this report are based on AECOM's experiences as part of the field demonstration phase (Task 2) of this research project.

Thermal Data Collection Recommendations

Equipment Selection and Rational

Task 2 included field testing of handheld and drone mounted thermal cameras at five bridge sites in Massachusetts and Rhode Island in order to determine effectiveness of concrete delamination detection. The field testing included portions of the following bridges:

- Bridge S-17-039 (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

Both handheld and drone mounted thermal cameras were able to identify concrete delaminations along the underside of bridge decks and have the potential to be a useful tool for bridge inspections. The handheld thermal camera equipment included the Flir E96, Flir E86, Flir E8, Flir C5, Fluke TiX580, and Seek Shot Pro. The drone mounted thermal camera equipment included the Parrot Anafi USA, Skydio X2, DJI Matrice 210 V2 with Zenmuse XT2, and DJI Matrice 300 with Zenmuse XT2.

Based on field testing of handheld thermal cameras, Flir handheld cameras provide a user friendly and effective experience. Out of the field-tested thermal cameras, the Flir E96 provided the best quality imagery and most user-friendly experience. This camera has the highest thermal resolution of the tested equipment at 640x480. The specifications for the E96 can be found in Appendix A.

The drone mounted thermal camera field testing primarily consisted of the Zenmuse XT2 which is a 640x512 resolution radiometric thermal camera with integrated 12 megapixel (MP) visual camera. The field testing also included limited use of the Skydio X2 and Parrot Anafi USA, both of which have integrated non-radiometric 320x256 resolution 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 specification for the

Zenmuse XT2 can be found in Appendix A. However, during the course of 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.

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 span. 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 1 and Table 1). A larger version of the flow chart can be found in Appendix B. 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 Departments of Transportation (DOTs) based on the additional costs and training requirements of drone programs. Different agencies and consultants will have different equipment available. Refer to Table 2 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 on the following page.

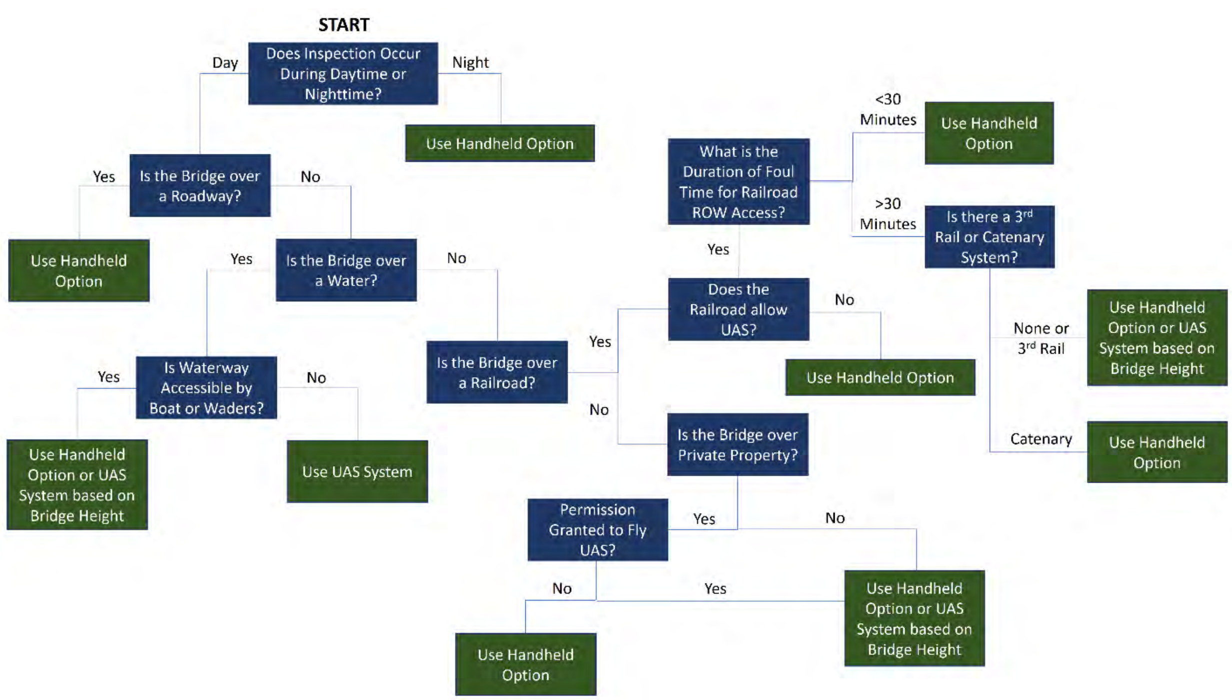

Figure 1 - Equipment Selection Flow Chart

Table 1 - 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 2 - 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'					✓	✓

Daytime or Nighttime

Handheld thermal cameras are recommended for nighttime operations in lieu of UAS flights. Visual imagery to cross check thermal is important for identifying delamination. The Flir E96 has a built-in lamp that can be set to act as a camera flash or the inspector could use a flashlight to illuminate the deck. Some drones can be outfitted with a lighting system, such as LumeCube, but this system may not provide adequate illumination. No lighting systems for drones were tested as part of this research project.

Additionally, strobes are required for nighttime flights per Part 107 regulations which may not be integrated or compatible with some drones. Depending on the specific bridge and nearby adjacent roadways, drone strobes may create a hazard for drivers in the vicinity.

Over Roadway

The majority of bridges crossing over roadways are overpasses with less than 20' of vertical clearance which are not the optimum condition for drone flights. Drones can be flown in these environments, but it does increase operational risk.

Part 107 regulations require that drone operations are not performed over moving vehicles and that night operations require an anti-collision light that is visible for at least 3 statute miles and flashes frequent enough to prevent collisions with other aircraft. Regulations would require partial or full traffic closures for drone flights over the roadway. The drone could also present a distraction for drivers on the roadway below which would negatively impact safety for the inspectors and traveling public.

While there is potential for the use of a handheld thermal camera to require traffic closures as well, there is less overall distraction to motorists.

Over Water / Accessible Waterway

Inspections over waterways can potentially use handheld or thermal cameras based on other considerations. Drone operations for multi-span bridges crossing waterways may require multiple launch/recovery positions or the use of a boat in order to maintain visual line of sight with the drone.

Waterway current should also be considered. If the current is too strong, it may not be safe for inspectors to use waders and may be difficult to keep a boat positioned underneath a bridge.

If the waterway is not accessible using waders or a boat, then a UAS system would be the best option in order to survey the underside of the deck without traffic control and an under-bridge inspection unit (UBIU). This will be dependent on there being adequate vertical clearance for the UAS to safely fly beneath the bridge.

Over Railroad / Railroad Allows UAS

Several railroads are privately owned so DOT staff will need to obtain permission to launch UAS from the rail corridors.

Depending on the railroad, track access may only be granted during overnight non-revenue hours. In this case, handheld thermal cameras are the recommended equipment. See the discussion for Daytime or Nighttime.

Another consideration for rail corridors, is the specific launch/recovery location. The steel rails are sources of electromagnetic interference (EMI) which can cause compass calibration issues. The more robust commercial drones, such as the DJI Matrice 210 or Matrice 300 have additional shielding to reduce this impact, but it may still occur. DOT staff should try to identify launch positions that are outside of the centerline of the tracks.

Duration of Railroad ROW Access

Railroads may grant limited access to the right of way (ROW) with varying durations. Limited windows of access would make the use of handheld thermal cameras preferable due to the amount of time required to transport and set up/break down a drone system.

For example, the DJI Matrice 210 case weighs over 25 pounds and requires two people to easily carry. The case has wheels, but the terrain may require it to be carried which will slow the time to travel from the track access site to the bridge. Drone set up includes installing landing gear, propellers, batteries, and the controller screen. Transportation to the site and set up/break down time will take away from access windows.

3rd Rail or Catenary

Railroads commonly have 3rd rail or catenary systems to power trains. The flow chart assumes that both 3rd rail and catenary systems would be de-energized during access.

Rail corridors with catenary systems would be best served with a handheld thermal camera as the catenary wires can provide a flight hazard for drones. The catenary also reduces the vertical clearance beneath the bridge.

Rail corridors with a 3rd rail can utilize either handheld or UAS mounted thermal cameras. The specific equipment should be selected based on the bridge height.

Private Property

At this stage in the flow chart, the bridge should just be crossing land without the other features previously covered, whether it is a privately owned property, state owned, or municipal owned. Drone operations require permission from the property owner for launch/recovery. If permission is not able to be obtained, the handheld thermal camera would need to be used.

Temperatures and Weather Conditions

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 C. The summary tables are divided into two separate tables based on the whether the data was for the Flir E96 or Zenmuse XT2. 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.
- 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 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. Linear trend lines were added for visual reference. Refer to Figures 2 and 3 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.

Some potential causes for the differences between the required temperature change for detection for 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; Bridge Identification Number (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.

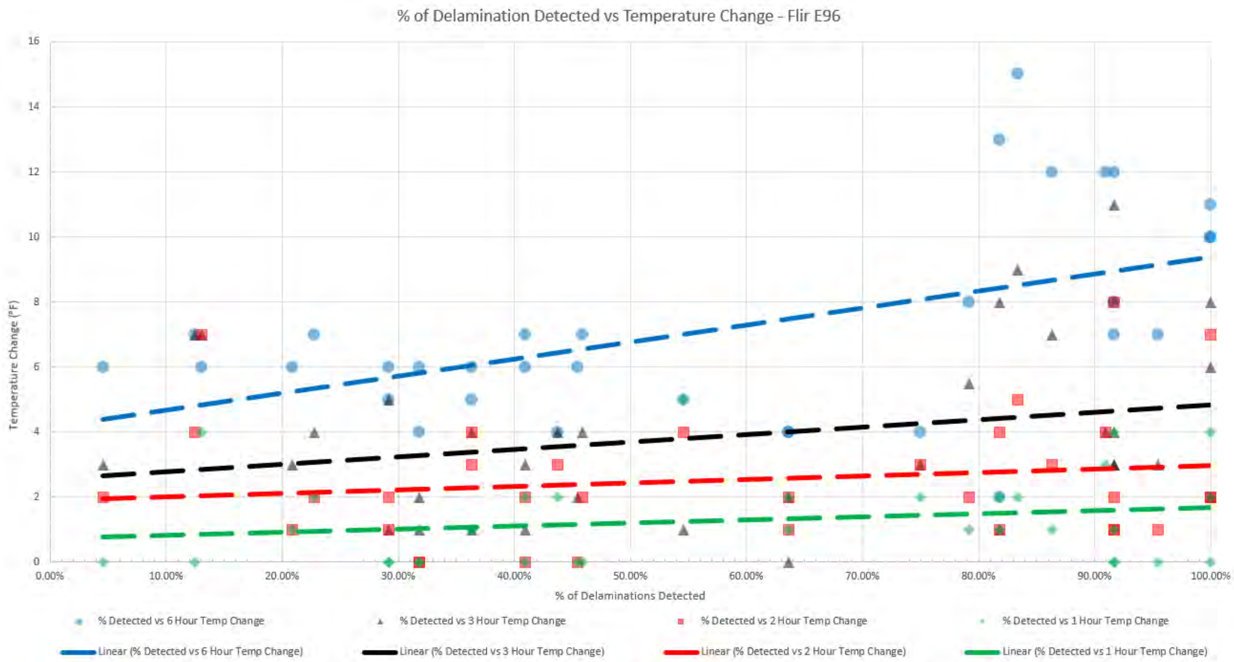

Figure 2 - Delamination Detection versus Temperature Change for Flir E96

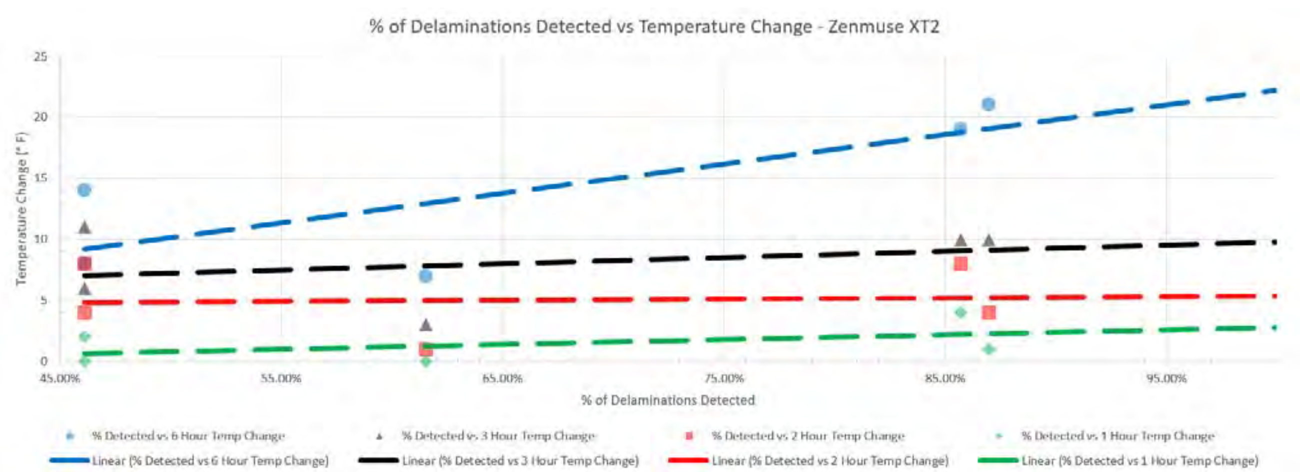

Figure 3 - Delamination Detection versus Temperature Change for Zenmuse XT2

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 UAS 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 likelihood of detection. 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. 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 is limited, and additional field testing may result in updated recommendations.

Recommended Field Inspection Protocols

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 the flexibility with being able 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 would be easy to try it a few times and go back to the existing traditional methods, DOT 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 followings:
    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 another 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 when the temperature span (referred to as scale in camera) is set in manual mode. Touching the screen will cause the camera to automatically adjust the thermal span 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 "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:
    a) Record photo files as 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 picture-in-picture (PIP) mode with the visual and thermal imagery displayed side by side.
5. Verify adequate global positioning system (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 4 through 6. Larger versions of the flow charts can be found in Appendix B. Discussion of the criteria utilized in the flow charts is discussed in the following sections.

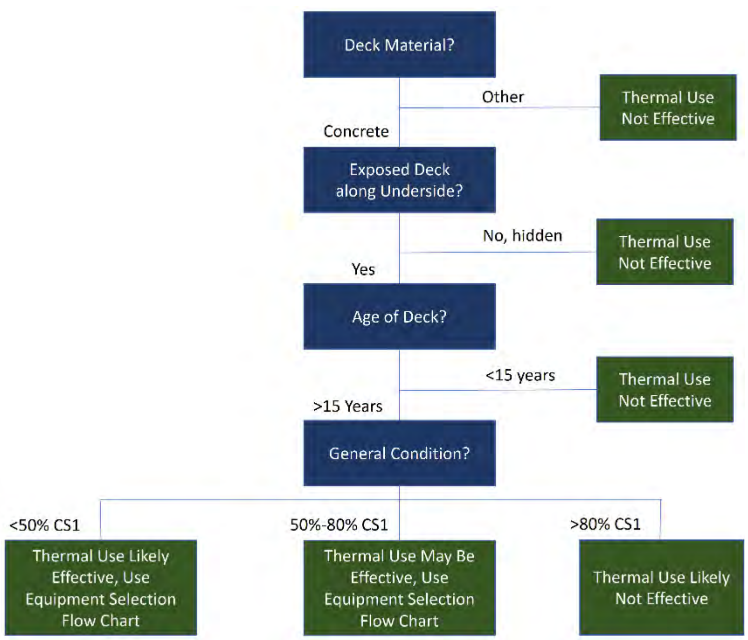

Figure 4 - Flow Chart to Determine Effectiveness for Deck Underside

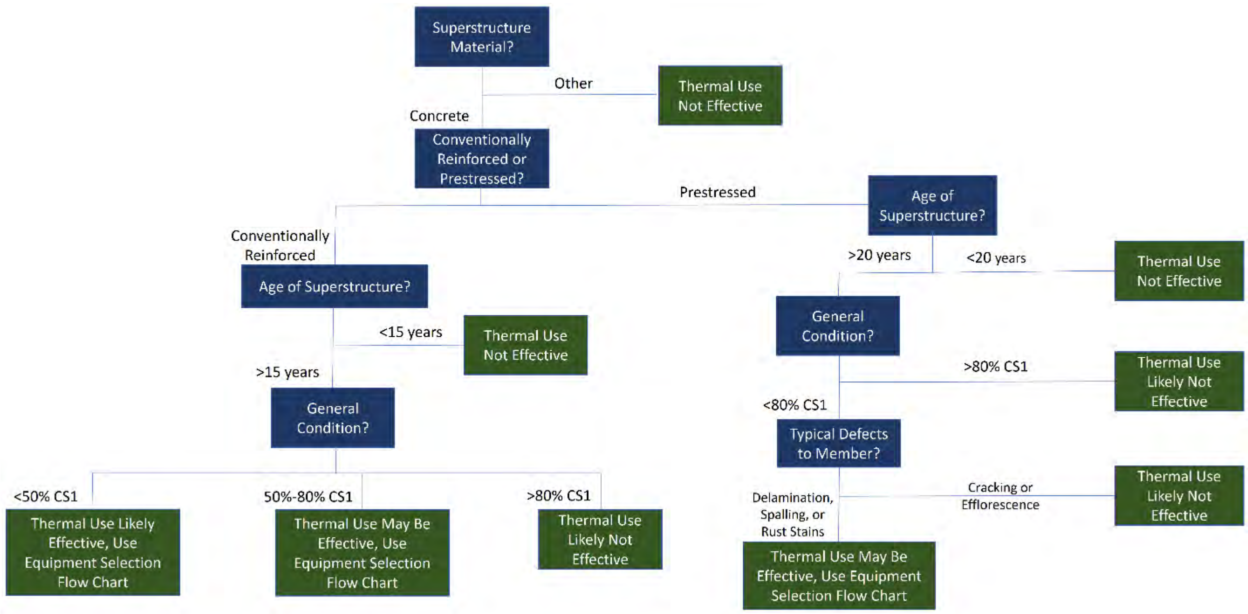

Figure 5 - Flow Chart to Determine Effectiveness for Superstructure Elements

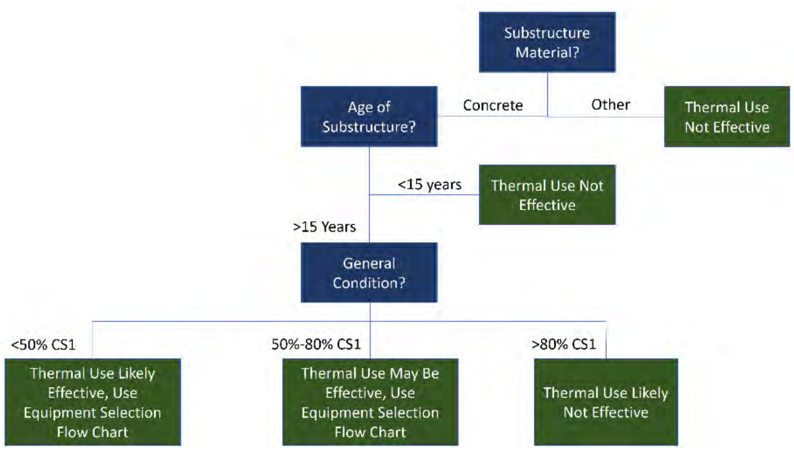

Figure 6 - Flow Chart to Determine Effectiveness for Substructure Elements

Bridge Material

The research project has focused on concrete bridges. Other types of materials were not tested and recommendations for these other materials are not included.

Age of Member

The age of a member is important because it correlates to the amount of deterioration that can be expected. Typically, deterioration is evaluated based on the American Association of State Highway and Transportation Officials (AASHTO) Manual for Bridge Element Inspection. There are national bridge elements (NBEs) for deck, superstructure, and substructure that are used to track deterioration on an element level basis. This system uses condition states (CS) to qualify deterioration as good (CS1), fair (CS2), poor (CS3), and severe (CS4). Deterioration curve values are used to predict the rate of change from one condition state (CS) to another, provided there is no intervention through maintenance/repair/rehabilitation. The deterioration curves primarily evaluate the condition based on age. Generic deterioration curves were reviewed as part of the flow chart development and considered for the age components of the flow charts. The deterioration curves for Element 12 – Reinforced Concrete Deck are included as Figure 7 below.

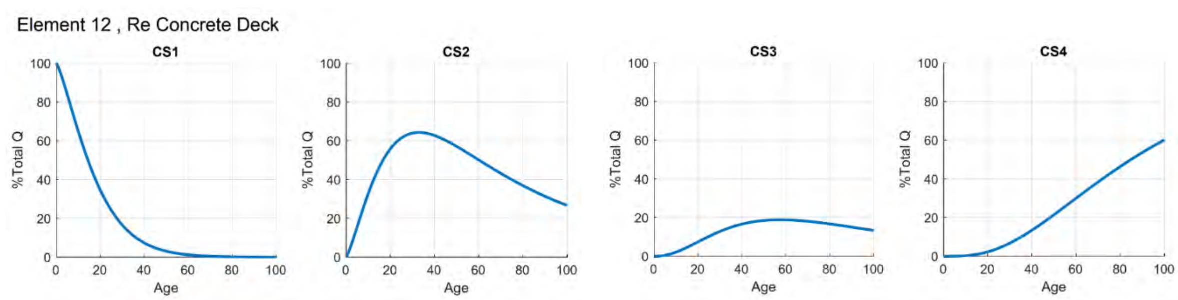

Figure 7 - Deterioration Curves for Reinforced Concrete Deck

Type of Reinforcing

Conventional reinforcing versus prestressing is considered as members with conventional reinforcing will have more extensive amounts of cracking which allows chlorides to contact reinforcing and cause steel corrosion. Prestressed members are designed so that under loading conditions the concrete has no or minimal tensile stresses that would cause cracking. Additionally, prestressed members are generally formed and cast in concrete plants with controlled environments. As a result, prestressing is generally higher quality than conventionally reinforced concrete cast in the field. This also contributes to the durability of prestressed members over conventional reinforcing. Prestressed members will take more time to develop deterioration.

General Condition

Regardless of the age and construction, existing deterioration should be considered when determining whether thermal imaging would be effective. Defects associated with reinforced concrete include delamination/spall/patched areas, exposed rebar, efflorescence/rust staining, cracking, abrasion/wear, distortion, settlement, scour, and damage.

As every bridge is different, deterioration will develop at different rates. The flow charts consider overall percentage of the element condition as follows:

<50% CS1 – Thermal anticipated to be effective
50% to 80% CS1 – Thermal may be effective
>80% CS1 – Thermal likely not effective

These percentages were chosen based on engineering judgement. Cracking, efflorescence, and delamination are the most common CS2 defects. Cracking and efflorescence are likely to form before delaminations which means that small percentages of CS2 will likely not indicate delamination.

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 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 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.

Thermal imaging should be used as a screen tool to identify potential delaminations in the bridge deck. 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 he believes 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 sketch. The work can be performed with two crew members but there will be much more inefficiency 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.

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.

Data collection for the underside of the bridge deck shall be performed in accordance with the temperature and weather recommendations within this interim 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.

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.

Thermal Data Analysis

The Task 2 Interim report included a discussion on the basics of thermography along with a brief discussion of overlays and settings. This included environmental factors as well as subject features that could affect temperature readings. Thermal data should be cross checked against visual imagery whenever possible to ensure that there are no false positive identifications of defects.

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

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 8 and 9).

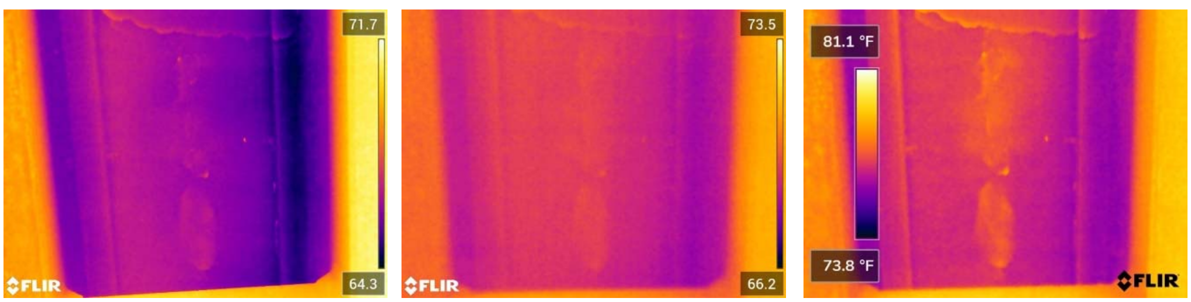

Figure 8 - Variations of Thermal Imagery for BIN 4E5, Location 7

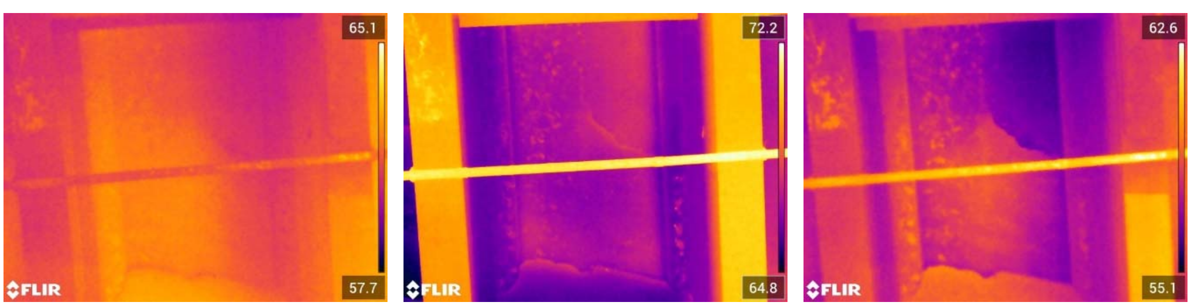

Figure 9 - Variations in Thermal Imagery for BIN 4E5, Location 11

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 "Thermal Analysis Software Packages" for additional information.

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 easier to distinguisher larger temperature changes (refer to Figure 10). Additionally, with the Zenmuse XT2, the thermal span can not 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.

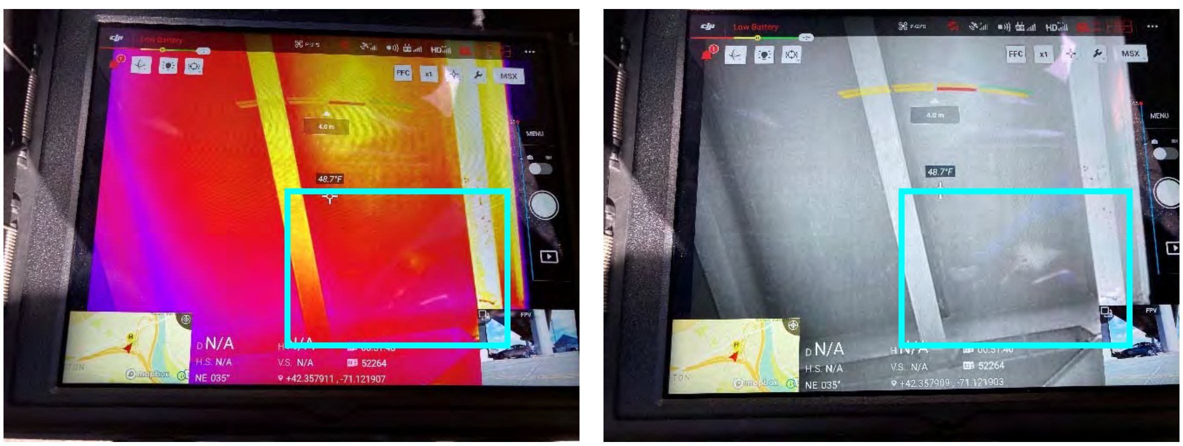

Figure 10 - Screen Shots of Ironbow and White Hot Color Palettes Showing Delamination

Figures 11 and 12 provide several examples of concrete delamination using automatic and manual temperature spans in different color palette.

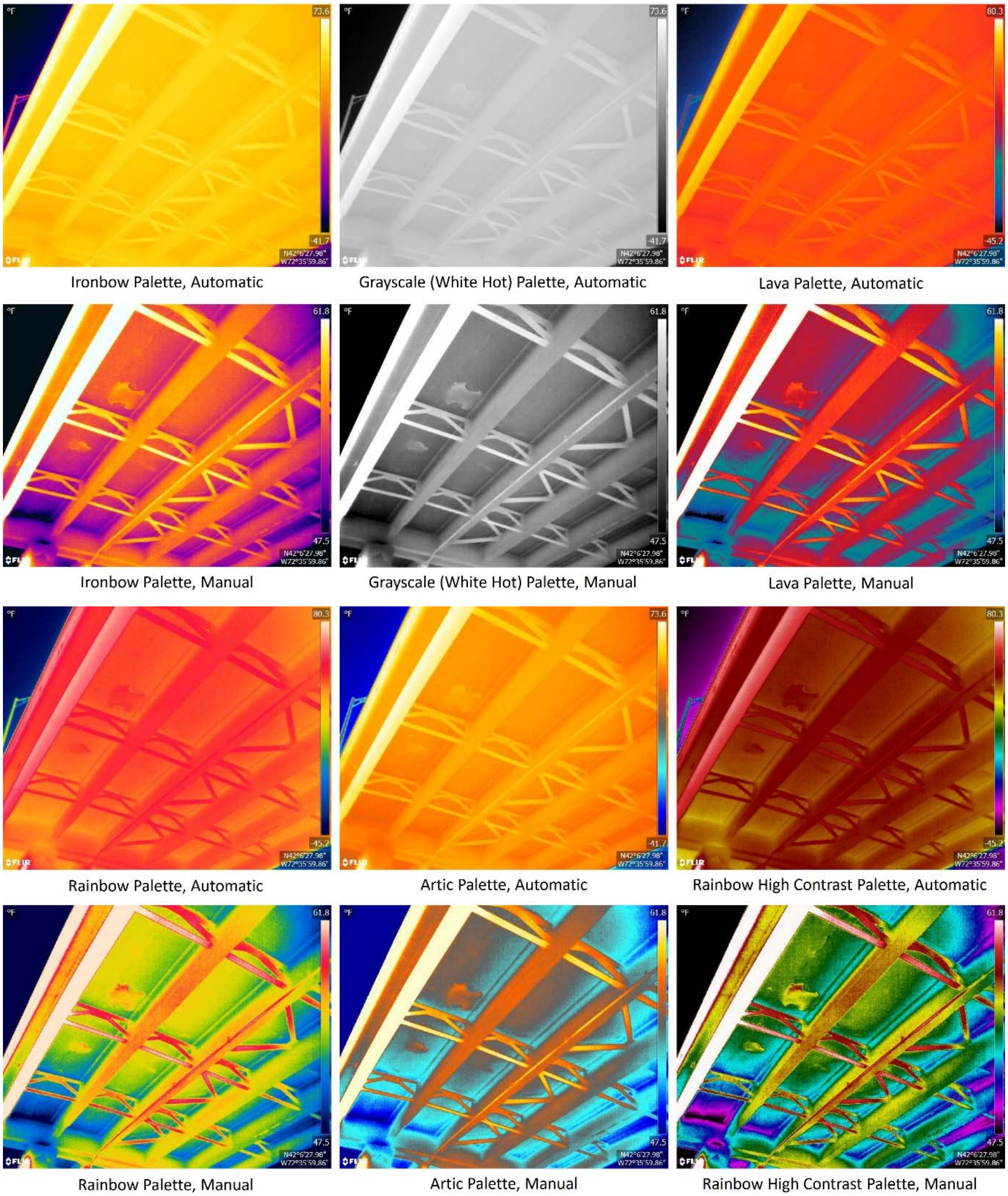

Figure 11 - Comparison of Different Color Palettes for Zenmuse XT2

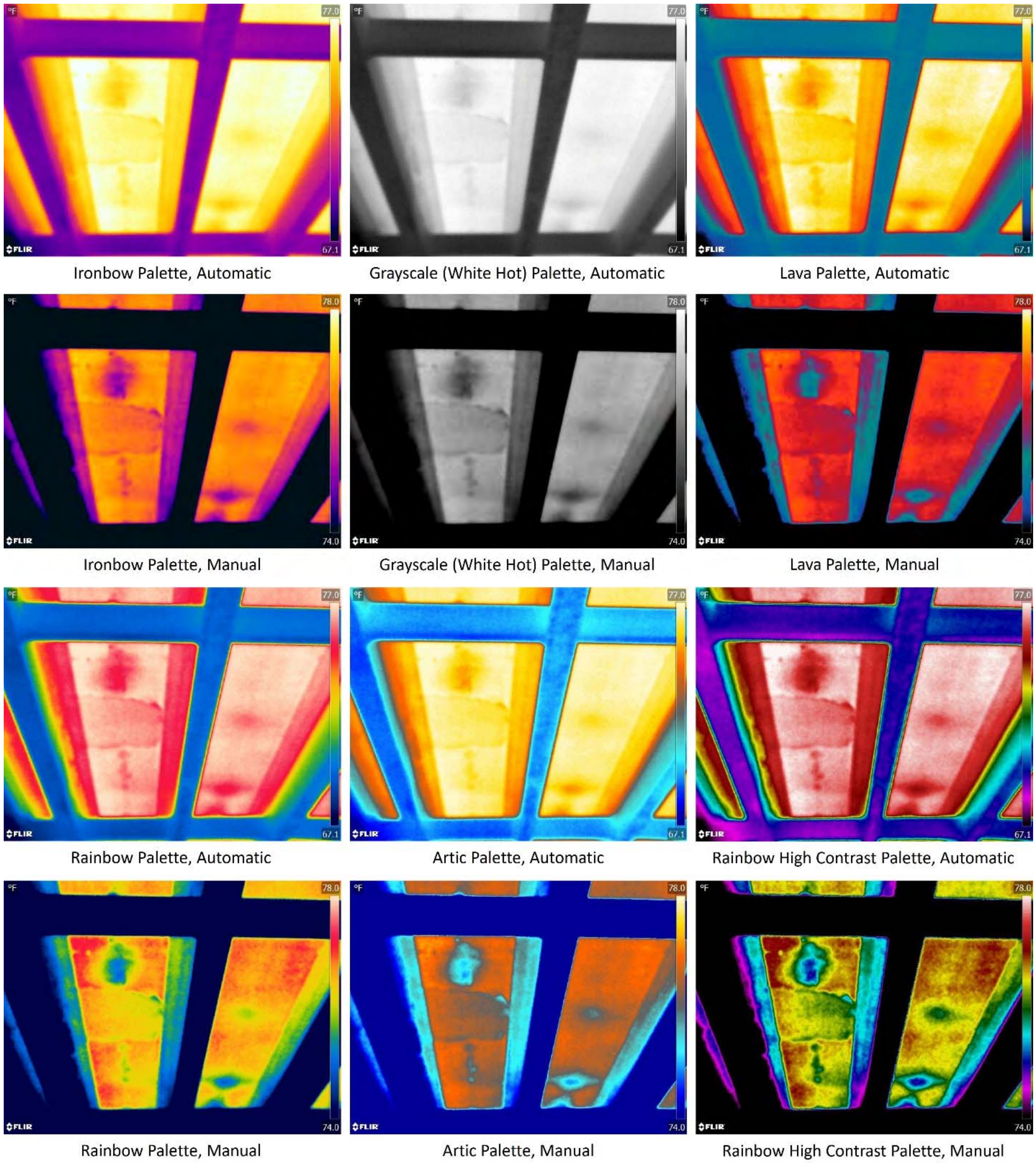

Figure 12 - Comparison of Color Palettes for Flir E96

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 is compatible with the 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 A. 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 13). An overview of the software package and basic processing steps are provided in Appendix D.

Figure 13 - 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 14.

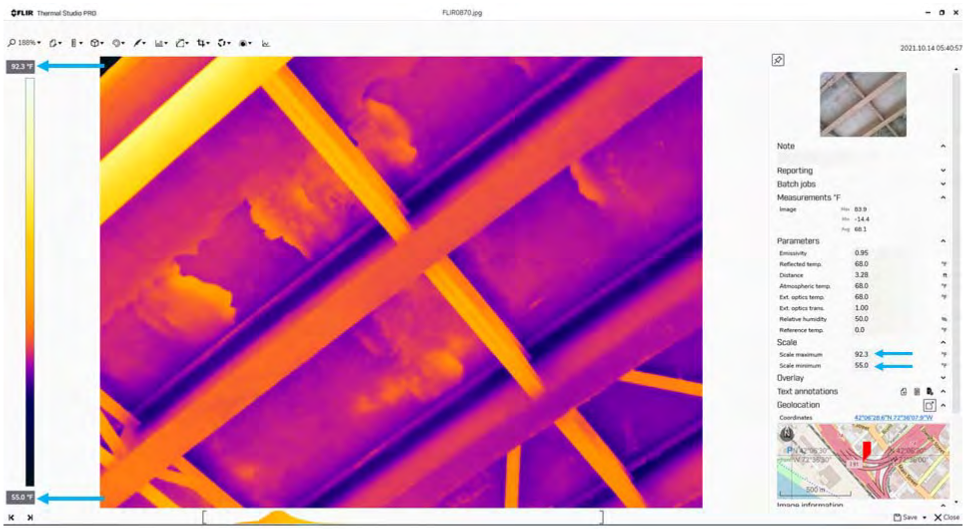

Figure 14 - Manual Entry for Minimum and Maximum Temperatures

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 15 below. The brackets ([ ] – indicated with green arrows in Figure 15) 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, they 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, it can be clicked and dragged to adjust the temperature span and level while leaving the existing temperature difference between minimum and maximum temperatures.

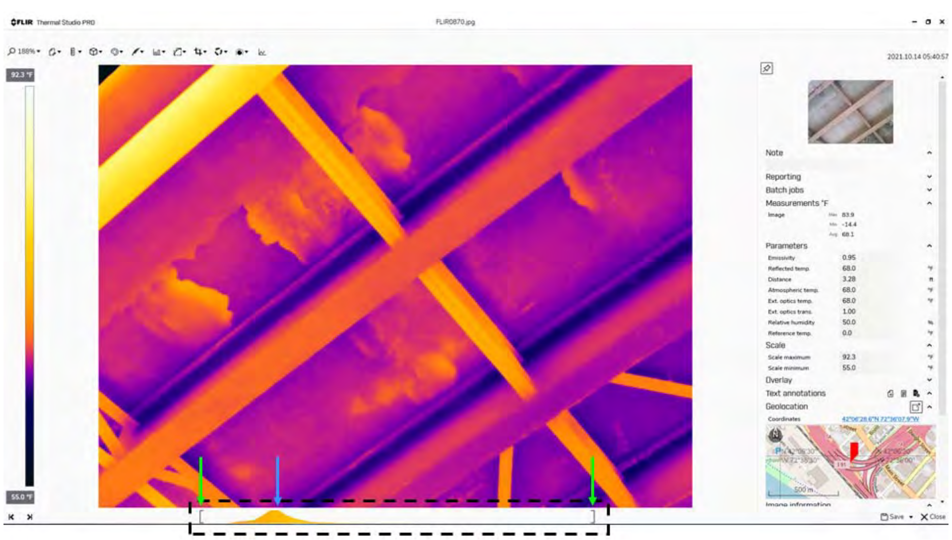

Figure 15 – Adjusting Temperature Values using Histogram

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.

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 interim report), even more storage space will be required.

General 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 [NBIS]. 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
- Bridge 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 DOT's 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.

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 16 through 18 show several examples of traditional inventory photos versus a drone image.

Figure 16 - Terrestrial versus Aerial Elevation of Girder Bridge

Figure 17 - Terrestrial versus Aerial Elevation of Steel Box Girder Bridge

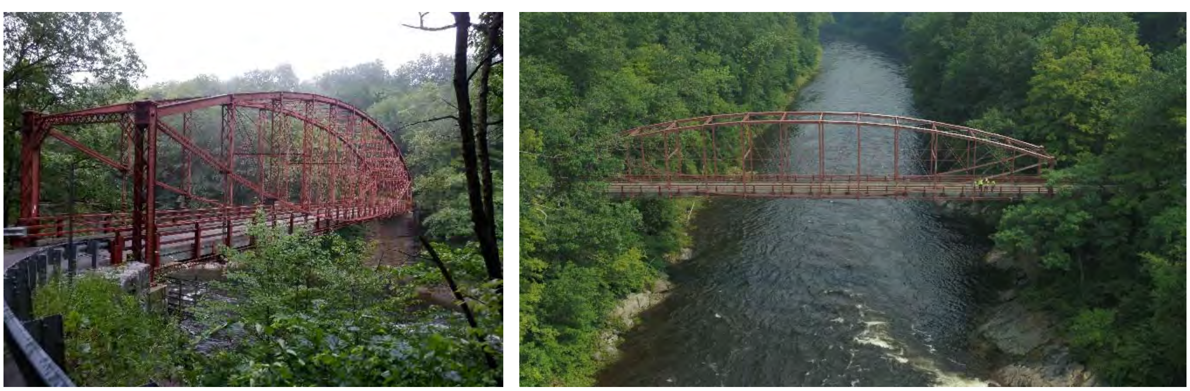

Figure 18 - Terrestrial versus Aerial Elevation of Truss Bridge

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 19 and 20).

Figure 19 - Terrestrial versus Aerial Image of Wearing Surface

Figure 20 - Terrestrial versus Aerial Image of Wearing Surface

Visual Screening Tool

Drones can function as an initial screen 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 which 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 to focus on and viewing angles.

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 21 and 22)
- Girders and floorbeams
- Arches, slabs, and rigid frames (refer to Figures 23 and 24)
- Bridge members extending above the bridge deck, such as decorative pylons, towers, secondary support trusses, ancillary structures (refer to Figures 25 and 26)
- Cable stays
- Roof and sidewall of covered bridges (refer to Figure 27)
- Tall piers

Figure 21 - Underside of Deck Overhang

Figure 22 - Underside of Deck


Figure 23 - Underside of Concrete Arch


Figure 24 - Underside of Concrete Slab

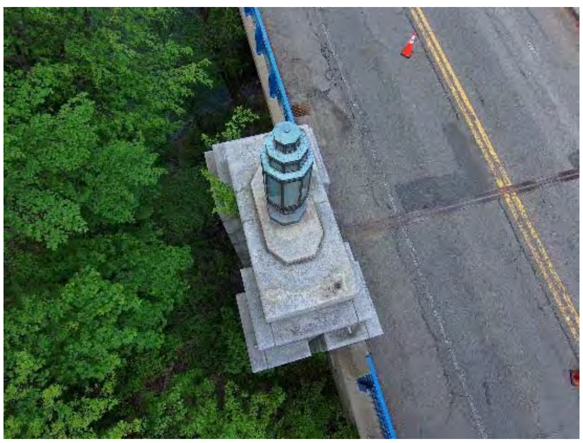
Figure 25 - Top of Pylon


Figure 26 - Counterweight Truss


Figure 27 - Roof of Covered Bridge

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 (refer to Figure 28). 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 28 - Aggradation with Vegetation Growth along Channel Upstream of Bridge

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. For this reason, this interim report does not include a detailed overview of protocols for drone implementation. However, a brief overview of planning steps is included for reference.

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 Federal Aviation Administration (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 29), online databases such as the FAA UAS Data ArcGIS map (see Figures 30 and 31), 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. AECOM's experience with Boston Logan International Airport has these requests being reviewed and approved in less than a week.

Figure 29 - Sectional Chart of CT, MA, RI

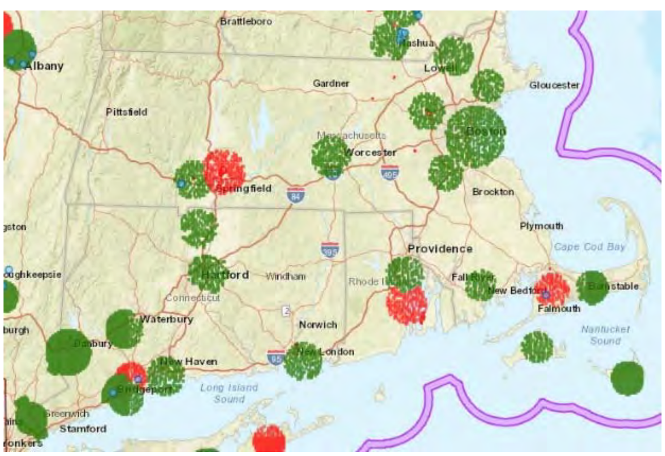

Figure 30 - FAA ArcGIS Map of CT, MA, RI

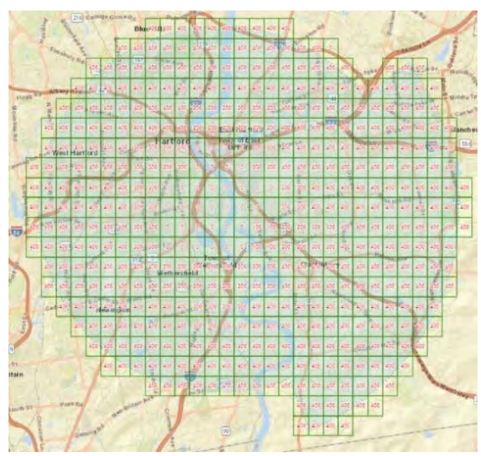

Figure 31 - ArcGIS Map of Brainard Airport in CT

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 32 and 33). 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 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.

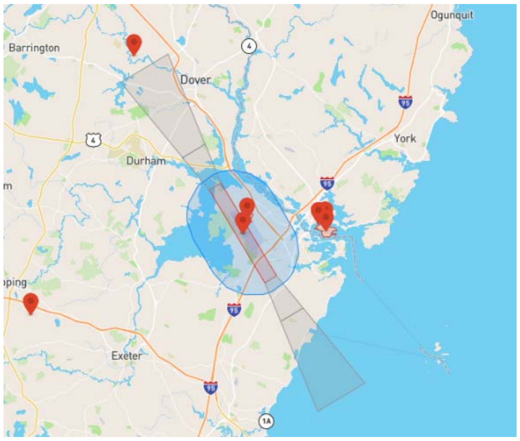

Figure 32 - DJI GeoZone Map of Pease International

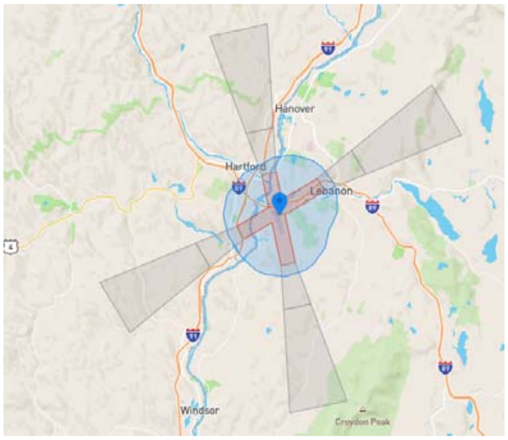

Figure 33 - DJI GeoZone Map of Lebanon Municipal Airport

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 DOT 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 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. Air space 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 enough batteries are not 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 as well as make sure the batteries and controllers are fully charged.

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 should be anticipated to be unpredictable adjacent to the bridge superstructure and substructure. In some cases, swirling winds can cause turbulence that can actually pull a drone towards the bridge structure
- Electromagnetic interference (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 interference or a 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.

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. If so, 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.

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 an 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 34 and 35). 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 34 - Different Exposure Compensation Settings

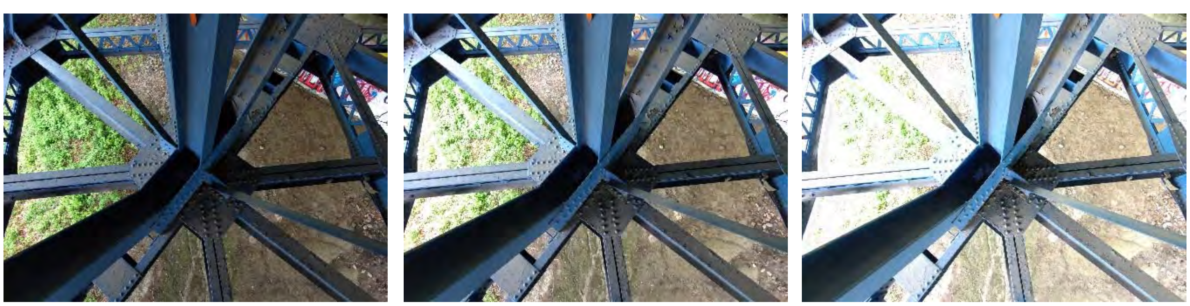

Figure 35 - Inadequate Visual Imagery due to Bridge Geometry and Lighting

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 36)
- Joints/gaps between adjacent box beam sections (refer to Figure 37)
- Lateral or cross bracing limiting access to stringers, floorbeams, or girders (refer to Figure 38)
- Built-up truss members and gusset plates (refer to Figure 35)
- Bearings that leave minimal height between the superstructure and substructure (refer to Figure 39)

Figure 36 – Limited View of Bottom of Girder Web and Top of Bottom Flange

Figure 37 – Limited View of Vertical Face at Gap between Box Beam Sections

Figure 38 - Lateral Bracing Limiting View of Stringers

Figure 39 - Limited View of Bearing and Top of 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 40). There are commercial products available in the form of glare resistance screen protectors and sun shades; however, this will vary on the specific drone model and controller (refer to Figure 41). If neither of these products are available, the inspector should try to position themselves in a shaded area. The imagery should be reviewed on a laptop in the field prior to complete field activities and demobilizing.

Figure 40 - Screen Glare on Skydio Enterprise Controller

Figure 41 - Sun Shield 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.

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.

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.

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 Low Altitude and Notification Capability (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

Cost Estimate

Cost estimates have been developed as part of this 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 3 and are further discussed below.

Table 3 - 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**

Training Costs

The training costs included in this section are based on the discussion in Section "Training Considerations." The training programs are anticipated to include 5 staff members from the DOT for a duration of two-days for thermography training and five-days for drone training (refer to Tables 4 and 5). It is assumed that the training will be performed with a mid-level engineer with between 5 to 10 years' experience and 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.

DOT 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 DOT staff, a consultant, or a vendor.

Table 4 - Thermal Training Costs

Thermal Training Costs								
Item	**Days**	**# Staff**	**Unit Cost***		**Unit**	**Subcost**	
DOT 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 DOT staff, no multiplier is applied. For trainer staff, a 2.6 multiplier is applied.*

Table 5 - Drone Training Costs

Drone Training Costs					
Item	**Days**	**# Staff**	**Unit Cost***	**Unit**	**Subcost**
DOT Staff - Training Time	5	5	$ 38.00	$/Hr	$ 7,600.00
DOT 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 DOT staff, no multiplier is applied. For trainer staff, a 2.6 multiplier is applied.*

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 6.

Table 6 - 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 7.

Table 7 - 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) 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.

Future Applications and Research

AECOM recognizes that there are additional technologies that complement thermal imaging and drones that have the potential to be beneficial tools for bridge inspections. Since these technologies were not included as part of the scope of this research project, this section will only provide a brief overview to spread awareness of their capabilities. It is recommended that state agencies look into these applications and consider for future research. These potential future applications discussed below include photogrammetric modeling and machine learning for data analysis.

Photogrammetric Modeling

Photogrammetric modeling of bridge structures to create a digital twin has the potential to be a valuable tool for inspection tracking and asset management. Photogrammetric models have been used to develop digital twins of bridges but there are limitations in regards to both data collection and data processing.

Photogrammetric modeling relies on distinct tie points in order to stitch photos together. If there are not enough distinct tie points in the images, the software can struggle to accurately stitch images together which can leave gaps in the final product or result in the model failing to be developed. The modeling process requires a large number of photographs in order to maintain sufficient overlap for the software to sufficiently process tie points. This requires multiple perspectives and angles in order to accurately model the subject geometry. Both terrestrial and drone imagery can be utilized in the development of photogrammetric models.

Data Collection for Photogrammetric Modeling

In general, photogrammetric modeling of visual imagery requires:

- Minimum 75% overlap for visual imagery
- Corners/edges captured from 3 or more angles

Based on the nature of bridges, data capture would be needed along the underside of the bridge. At the time of this report, AECOM was only aware of one automated flight software, Skydio 3D Scan, that might be capable of performing automated flights for data capture along the underside of a bridge. AECOM did not perform testing of this flight software to confirm. It should be noted that Skydio 3D Scan is limited to Skydio drones and does not include thermal data collection. Because of the limited automated flight software packages, flights to perform data collection along the underside of bridge decks will need to be performed manually.

Thermal imagery presents a greater challenge for photogrammetric modeling due to the limited size of a thermal image. Data captured for thermal modeling should include 90% overlap. This overlap would be difficult to achieve with manual flights underneath a bridge deck. Additionally, a radiometric thermal sensor with a thermal span that is able to be set manually would be needed for the application. The use of a thermal camera that is only capable of an automatic thermal span based on the image would be problematic since any visible sky near the deck overhangs or exterior bays will greatly skew the thermal span. Underside data collection will also present a challenge for bridges with limited vertical clearances since there will be limited portions of the deck visible in each thermal image which may hinder the software from identifying an adequate number of tie points.

Photogrammetric Modeling Data Processing and Products

Photogrammetric modeling can be performed with several different commercially available software packages, including Bentley Context Capture as well as cloud-based platforms including Drone Deploy, Pix 4D, and GNext Labs. Each software platform has different processes and settings for developing photogrammetric models. Not all platforms will be capable of processing a 3d model for the underside of a bridge.

The model accuracy and quality will vary based on the original image quality (megapixels and focus), ground sample distance (physical distance between the center of image pixels), image overlap, consistent lighting conditions, and user settings.

Benefits and Applications of Photogrammetric Modeling

The bridge model provides a visualization of the overall bridge condition. The model can be used to extract orthomosaic images of different faces of the model. These orthomosaic images help provide context for the overall condition, which can be lost since inspection reports focus on the deficiencies. This helps to provide a “big picture” view. It also provides an exact image of the structural condition which can be useful for report documentation in lieu of traditional deficiency sketches, where hand drawn field sketches are translated into final report sketches using AutoCAD. Traditional field sketches can be time consuming to develop and may not be entirely accurate due to the subjective nature of documenting cracking, spalling, and delaminations by different bridge inspectors.

The final photogrammetric model can also be a useful tool for quantification of defects, as both length and area can be determined from the model. There is potential for 3D models to eventually serve as a reporting tool, in lieu of traditional text-based reports. Cloud based platforms are capable of annotations which can be printed into a pdf report, however, at this time, they are not designed to be utilized for bridge inspection reporting. Over time, with guidance from the bridge inspection industry, these platforms could become more aligned with bridge inspection needs.

The drone model and output orthomosaics can be used for a variety of different data processing methods. There are several companies that are working on machine learning and artificial intelligence in order to develop automated defect identification and quantification processes. This will be discussed later in the “Machine Learning for Data Analysis.”

Additional manual data processing is possible through other commercially available software, such as Matlab. Feature extraction processes can be used to highlight visible deficiencies such as cracking and spalling. If multiple data sets are available, processes like digital image subtraction can be applied to identify the change (typically worsening) of existing defects and deterioration over the time between the data sets.

Photogrammetric Modeling Limitations

It is important to understand the limitations of the technology. Photogrammetric model will not be successful for all types of bridge structures. Some examples which would likely result in models with gaps or holes in the model are discussed below.

- Steel members are generally more difficult for these software platforms to process due to the matte finish and similar appearance of the paint protective systems. The protective coating has a very uniform appearance which makes it difficult for the software to establish tie points.
- Large bridges that take hours or even multiple days to fly will have changing lighting and shadows. These varying lighting conditions can cause issues with model development as well as machine learning models that use photos for training.
- Girder bridges consisting of w-shapes can hinder data collection. The outstanding legs of the bottom flanges will cause areas along the bottom of the web and top face of the bottom flange to be missed during data capture. The pilot can potentially capture these areas by flying in between girders but that will increase the required time for data collection and may not be possible depending on the girder spacing.

At present, concrete and masonry construction will provide the best opportunity for a successful model. Bridges without any obstructions or outstanding features to block views (i.e. rigid frame, tee-beam, box beam, arch, slabs) would be the best starting point for evaluating photogrammetric modeling.

There are also limitations on the client end as well:

- Photogrammetric modeling is not a substitute for an NBIS inspection. While it does provide additional high-quality data, there will be additional costs. At present, the use of photogrammetric modeling may be more effective for bridge rehabilitation or special condition monitoring projects than NBIS inspection.
- Models require large amounts of digital data which will likely cause data storage issues. While cloud-based platforms remove some data size issues for limited scope applications; an entire bridge inventory would be a large amount of data that is not practical.
- Cloud based platforms may not meet data security requirements.
- There is minimal guidance on the topic of integrating digital twins into existing inspection and asset management workflows.

Future research in the area of photogrammetric modeling and the use of digital twins could include development of autonomous flight data collection software, guidelines for capture and processing, development of cloud-based analysis software, and guidelines for implementation of digital twins into DOT asset management systems.

Machine Learning for Data Analysis

An option for identifying bridge defects from thermal and/or RGB imagery is to develop an automated image analysis model to increase efficiency and standardize the process. As these automated models are an innovative technique, it is important to look at implementation in both terms of short term and long-term application strategies. As a more short-term application, these automated analysis models have to potential to drastically increase efficiency of inspections through identifying and quantifying defects automatically rather than the inspector taking measurements of each defect. A longer-term goal would be to develop a model capable of identifying delaminations that are not visually apparent.

An image is a specific type of dataset made up of continuous pixels that have unique numerical values for each spectral band or layer of the image. Spectral bands refer to the various portions of the electromagnetic spectrum that the camera or sensor captures data. A standard camera captures imagery in red, green, and blue bands while thermal sensors image in the thermal region of the electromagnetic spectrum to produce 1-band images. Automated image analysis employs remote sensing techniques that leverage the differences in pixel values in the image across all spectral bands (i.e. red, green, blue, and thermal) to classify the pixels into specific categories such as defect and non-defect. There are many methods that are available to perform this analysis known as image classification including machine learning models which will be discussed in greater detail below.

There are distinct data requirements for building and deploying an automated image analysis model. Most importantly is the acquisition of training and testing data for model development and accuracy assessment. For a model that detects bridge defects from RGB and/or thermal imagery, this training data would need to be images of defects that have been marked up digitally by an expert delineating the boundaries of the defect. Ideally, the training data would contain many images per defect type (ex: delamination, cracking, etc.) that cover the full range of visual possibilities for that defect.

Large number of training samples are required for model training and “internal” parameter tuning. It is important to note that there are limitations for training data. For example, delaminations are typically outlined and hatched by inspectors after sounding with additional mark ups being added each round of inspection. If these marked up images were used to train an automated model, then the model would rely on the chalk for the delineation because it is a distinct visual pattern in the imagery. The automated model would not be using visual or thermal imagery to identify the defect digitally but rather the outline and hatching. In order to initiate the process to build an automated image classification model for bridge defect detection, images of the defects prior to the chalk markup would be needed then the chalk markup images could be used to assist with delineating the defects digitally.

A large amount of training images are necessary for model development because a portion of these images must be held out to assess the accuracy of the automated model. These images are held out during the training of the model then used as an independent dataset to assess how well the model performs on unseen images. In addition to “internal” parameter tuning, most machine learning models require the step of hyperparameter tuning (i.e. investigating different overall model parameters like the number and size of the hidden layers in a neural network) and an additional portion of training data is held out to examine the impact of these hyperparameter values on model accuracy. In order to prevent model overfitting, the training samples used to train the model must be different than hyperparameter tuning samples and samples used for accuracy assessment. Ideally, any image classification model should include several hundreds of training samples for each class or in this case defect type. These training samples should also cover all possible visual representations of the defect, including different orientations and different lighting. Model training can be an iterative process where additional training data is added later to increase the accuracies of specific classes where the model is not performing as well.

Image Classification Methods for Machine Learning

There are a multitude of methods available for automated image classification on RGB and/or thermal imagery, with many that have proven successful for classifying bridge defects. As mentioned above, image classification models utilize the data stored in imagery to assign specific classes to image features, such as defect and non-defect. There are initial image pre-processing steps that can improve image classification results which have proven useful for delineating bridge defects. The first are edge-detection algorithms which identifies boundaries in imagery by changes in the brightness values of the images. Edge-detection algorithms have proven successful for delineating cracks on bridges using Unmanned Aircraft System (UAS) data (Feroz & Abu Dabous, 2021). Edge-detection is often not computationally intensive thus can be applied quickly and accurately but the use is limited for other types of defects besides crack detection. Object-based image analysis (OBIA) considers the spectral and spatial characteristics of surrounding pixels by incorporating similar pixels into a homogeneous image object to use as the unit of analysis. Pixels are an arbitrary unit of analysis for image classification as it can contain mixed signals from surrounding areas or within the pixel itself (Jensen, 2007). By contrast, image objects represent more relevant units where classification into defect type can take place more easily. To employ OBIA the imagery is processed using a method called image segmentation that generates digital boundaries of the image objects. Image segmentation can be a computationally intensive processing step, but OBIA is an extremely useful prior step to classification especially for UAS data which can contain high amounts of noise. OBIA has also proven successful as a method towards classifying several types of bridge defects (Zollini et al., 2020).

The final step in an automated image analysis model for delineating and classifying bridge defects is image classification. Image classification takes the image and assigns a categorical variable or class to each unit of the image (i.e. pixel or image object). If attempting to assign a numerical value to the image units, an image regression model would be performed instead of classification. There are many available methods for image classification including both parametric methods like linear regression and non-parametric methods such as machine learning models. Image classification can be either supervised or unsupervised. Supervised classification requires the model be trained with ground truth or manually labeled data samples, in which the desired outcome is already defined by a supervisor. An unsupervised method would use unlabeled data and attempt to identify hidden patterns in the data set, for which the number of output classes is predefined, but the definitions of those classes are not. Image classification utilizes predictive variables calculated from the input image to predict the assigned class. For pixel-based classification, these variables are limited to the pixel values for each band of the image. For object-based classification, additional predictive variables can be calculated due to objects being made up of several pixels. For example, statistical metrics such as mean, minimum, maximum, and standard deviation of the band values as well as more advanced metrics like texture and geometry. Depending on the statistical nature of the image dataset and predictive variables, such as the distribution of values across bands, different methods will lead to better success than others. During the model selection phase, it is important to test multiple methods and have a robust understanding of the input data to ensure the optimal method is used. It is also possible to combine several models, known as an ensemble method, that make up for the weaknesses of each model to increase the accuracy of the prediction. Classification models are evaluated based on several metrics such as overall accuracy, kappa coefficient, and confusion matrix.

With the recent advent of artificial intelligence, machine learning techniques for image classification and regression have revolutionized the field of remote sensing (Maxwell et al., 2018). Machine learning algorithms are powerful because they can detect patterns that are too complex for human understanding. This characteristic can also be a weakness of machine learning models because they are often a black box and it is difficult to derive meaning from how the classification works.

There have been several studies that successfully applied machine learning models to UAS data of bridges such as structural element identification (Perry et al., 2020) and damage identification (Jeong et al., 2022). Some examples of popular image identification machine learning models are:

- Random Forest
- Support Vector
- Artificial Neural Networks, especially Convolutional Neural Networks
- K-Nearest Neighbor

Supervised machine learning methods normally require a higher number of training samples when compared to parametric methods to perform well, particularly neural networks and deep learning models. In addition, machine learning models are often computationally intensive leading to higher processing time compared to parametric methods.

Commercially Available Machine Learning Platforms

Several companies have been developing machine learning platforms for defect identification and quantification. Additionally, universities and/or consulting firms can develop machine learning programs as well.

AECOM has identified several packages that may be beneficial to investigate and evaluate for bridge inspection applications. AECOM has not utilized these products or had any informational meetings with the developers, so information included below is based on product information available online. These platforms include:

- Esri ArcGIS – Pavement Crack Detection Deep Learning Package: This is an add-on for ArcGIS Pro, ArcGIS Image Server, and ArcGIS API for Python. The package focuses on crack detection within bituminous asphalt which may provide useful for top of deck inspections.

- Fujifilm – Infrastructure Photo Analysis Services: This platform is a cloud-based platform that is currently in development and available as a Beta program. The platform allows the user to upload imagery which is then processed to be stitched together as an orthomosaic with cracks color coded based on width and length. The platform will provide an excel summary sheet, CAD (dxf file), stitched imagery (JPEG) with and without crack markings shown.
- Aren, Inc. – Infrastructure Management Platform: This platform is a cloud-based platform that can identify and quantify defects. The platform can provide an excel file of the defects as well as stitched imagery with defect markings.

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Appendix A

Product Specifications

FLIR

FLIR Exx-Series

ADVANCED THERMAL IMAGING CAMERAS

SPECIFICATIONS

Model	E54	E76	E86	E96
IR resolution	320 × 240 pixels	320 × 240 pixels	464 × 348 pixels	640 × 480 pixels
Resolution with UltraMax® enhancement	—	307,200 pixels	645,888 pixels	1.2 megapixels
MSX® image enhancement	Yes: details from visual camera add depth and perspective			
Built-in visual camera	5 MP, fixed focus, with built in LED light			
Thermal sensitivity	<40 mK @ 30°C (86°F)	<30 mK @ 30°C (86°F), 42°lens	<30 mK @ 30°C (86°F), 42°lens	<30 mK @ 30°C (86°F), 42°lens
Temperature range	-20°C to 120°C (-4°F to 248°F); 0°C to 650°C (32°F to 1202°F)	-20°C to 120°C (-4°F to 248°F); 0°C to 650°C (32°F to 1202°F)	-20°C to 120°C (-4°F to 248°F); 0°C to 650°C (32°F to 1202°F); 300°C to 1500°C (572°F to 2732°F)	-20°C to 120°C (-4°F to 248°F); 0°C to 650°C (32°F to 1202°F); 300°C to 1500°C (572°F to 2732°F)
Optional temperature range	—	300°C to 1000°C (572°F to 1832°F)		
Accuracy	±2°C (±3.6°F) or ±2% of the reading			
Focus modes	Manual	Continuous laser distance meter (LDM), one-shot LDM, one-shot contrast, manual	Continuous LDM, one-shot LDM, one-shot contrast, manual	Continuous LDM, one-shot LDM, one-shot contrast, manual
Digital zoom	1–4x continuous			1–8x continuous
Measurement tools	3 spotmeters in live mode, 1 area meter in live mode	3 spotmeters in live mode, 3 area meters in live mode		
Measurement presets	None, center spot, hot spot, cold spot, 3 spots, hot spot-spot*	None, center spot, hot spot, cold spot, User Presets 1&2		
Available lenses	None (fixed lens)	14°, 24°, 42°, macro (2x)		
Lens identification	—	Automatic (FLIR AutoCal™)		
1-Touch Level/Span	Yes: automatic contrast enhancement			
Laser pointer	Yes			
Laser distance meter	—	Yes		
Area measurement information	—	—	Yes	
On-camera routing software	FLIR Inspection Route™ — enabled			
On-camera report building	Voice annotation and GPS tagging to images and video; on-screen text; sketch on infrared images from touchscreen			
FLIR software integration	FLIR Thermal Studio Starter, FLIR Thermal Studio, FLIR Thermal Studio Pro, FLIR Research Studio			
Radiometric JPEG	Yes			
IR, radiometric, visual video recording	Yes			
IR, radiometric, visual video streaming	Yes, over UVC (radiometric, non-radiometric, visual) and Wi-Fi (non-radiometric, visual)			
Communication modes	USB 2.0, Bluetooth, Wi-Fi, DisplayPort			
METERLiNK®	Yes			
Display	640 × 480 pixels (VGA) Dragontrail® touchscreen			
Drop-testing	2 m (6.6 ft)			
Battery operation time	>2.5 hours, typical use			

*Hot spot to center spot Delta measurement

Specifications are subject to change. For the most up-to-date specifications, please visit flir.com.

FLIR AutoCal^{TM} Lenses

FLIR E76, E86, and E96 camera are compatible with all our interchangeable AutoCal lenses. The camera automatically recognizes when a new lens is attached and launches a wizard to begin auto-calibrating the camera with the lens—no need to send the camera in for service. This helps ensure the camera always produces high-quality images and precise thermal measurements.

WHAT LENS DO YOU NEED?

14°, 29 mm lens: this telephoto lens has a narrow field of view for precise focus and crisp imaging of distant targets.

24°, 17 mm lens: often considered the "standard" lens, the 24° × 18° field of view allows users to remain a safe distance from energized equipment (e.g. 3 m/6.6 ft) while still obtaining a crisp focus on smaller targets.

42°, 10 mm lens: this wide-angle lens captures the largest field of view for imaging buildings, roofs, or other areas where it's important to gather the most information in a single image.

THE Exx-SERIES and FLIR THERMAL STUDIO PRO

EMPOWERED WITH REPORTING SOLUTIONS TO STREAMLINE INSPECTIONS

Exx-Series cameras are the first FLIR models to come with our exclusive Inspection Route Camera Option automatically enabled in the camera.

Designed for thermographers who regularly inspect large numbers of objects over the course of a day, FLIR Inspection Route guides the user along a pre-defined route of inspection points so they can collect images and data in a structured manner.

The route begins in FLIR Thermal Studio Pro software, where users build their plan using the Route Creator plugin. They can include as many inspection targets as needed and organize them for maximum efficiency. Once they export the completed route to the Exx camera, they're ready to begin the day.

The predefined route guides the user's on-site movement to each inspection asset, automatically collecting and organizing saved images for a seamless import into FLIR Thermal Studio Pro. By ensuring that nothing is missed and that all inspection results are organized from start, the suite of FLIR inspection software speeds up inspections, improves organization, and simplifies reporting.

Learn more about FLIR Thermal Studio Pro, the FLIR Route Creator Plug-in, and the FLIR Inspection Route Camera Option at FLIR.com.

www.flir.com/exx-series

Specs

General

Name	Zenmuse XT2
Dimensions	With 25 mm lens: 123.7×112.6×127.1 mm With other lens: 118.02×111.6×125.5 mm

Gimbal

Angular Vibration Range	±0.01°
Mount	Detachable
Controllable Range	Tilt: +30° to -90° Pan: ±320°
Mechanical Range	Tilt: +45° to -130° Pan: ±330° Roll: -90° to +60°
Max Controllable Speed	Tilt: 90°/s Pan: 90°/s

Thermal Camera

Thermal Imager	Uncooled VOx Microbolometer
FPA/Digital Video Display Formats	640×512 336×256
Digital Zoom	640×512: 1x, 2x, 4x, 8x 336×256: 1x, 2x, 4x
Pixel Pitch	17 μm
Spectral Band	7.5-13.5 μm
Full Frame Rates	30 Hz
Exportable Frame Rates	<9 Hz
Sensitivity (NETD)	<50 mk @ f/1.0
Scene Range (High Gain)	640×512: -25° to 135℃

	336×256: -25° to 100℃
Scene Range (Low Gain)	-40° to 550℃
File Storage	MicroSD card*
Photo Format	JPEG, TIFF, R-JPEG
Video Format	8 bit: MOV, MP4 14 bit: TIFF Sequence, SEQ**

Visual Camera

Sensor	1/1.7" CMOS Effective Pixels: 12 M
Lens	Prime lens Focus at 8 mm FOV 57.12°× 42.44°
Digital Zoom	1x, 2x, 4x, 8x (Live View Only)
Photo Formats	JPEG
Video Formats	MOV, MP4
Video Resolutions	4K Ultra HD: 3840×2160 29.97p FHD: 1920×1080 29.97p
Working Modes	Capture, Record, Playback
Still Photography Modes	Single Shot Burst Shooting(3/5 frames) Interval (2/3/5/7/10/15/20/30 sec)
Video Caption	Supported
Anti-flicker	Auto, 50 Hz, 60 Hz
Storage	MicroSD card Max capacity: 128 GB. UHS-3 required Recommended model: Sandisk Extreme 16/32 GB UHS-3 microSDHC Sandisk Extreme 64/128 GB UHS-3 microSDXC
Supported File System	FAT 32 (≤32GB), exFAT (>32GB)

Image Processing & Display Control

Image Optimization	Yes
Digital Detail Enhancement	Yes
Polarity Control (Black Hot/ White Hot)	Yes

Models – Lens And Resolution Options

Note

The SD card, which is located near the lens, is used to store TIFF Sequence and SEQ infrared RAW video only. T
format footage will be stored in the other SD card.

*It is recommended to use ImageJ to play the TIFF Sequence video and Flir Tools to play SEQ video

Specs

General

Weight	Zenmuse H20: 678±5 g Zenmuse H20T: 828±5 g
Dimensions	Zenmuse H20: 150×114×151 mm Zenmuse H20T: 167×135×161 mm
Ingress Protection Rating	IP44
Operating Temperature	-20° to 50° C (Temperature Measurement is only available between -10° to 50° C)
Storage Temperature	-20° to 60° C
Laser Safety	Class 1M (IEC 60825-1:2014)
Supported Aircraft	Matrice 300 RTK

Gimbal

Angular Vibration Range	±0.01°
Mount	Detachable
Controllable Range	Pitch: -120° to +30° Yaw: ±320°
Mechanical Range	Pitch: -132.5° to +42.5° Yaw: ±330° Roll: -90° to +60°

Zoom Camera

Sensor	1/1.7" CMOS, 20 MP
Lens	DFOV: 66.6°-4° Focal length: 6.83-119.94 mm (equivalent: 31.7-556.2 mm) Aperture: f/2.8-f/11 (normal), f/1.6-f/11 (night scene) Focus: 1 m to ∞ (wide), 8 m to ∞ (telephoto)
Focus Mode	MF/AF-C/AF-S
Exposure Mode	Auto, Manual

Exposure Compensation	±3.0 (1/3 increments)
Metering Mode	Spot metering, Center-weighted metering
AE LOCK	Supported
Electronic Shutter Speed	1 ~ 1/8000 s
ISO Range	Video: 100 - 25600 Photo: 100 - 25600
Video Resolution	3840x2160@30fps, 1920x1080@30fps
Video Format	MP4
Video subtitles	Supported
Photo Size	5184 × 3888
Photo Format	JPEG

Wide Camera

Sensor	1/2.3" CMOS, 12 MP
Lens	DFOV: 82.9° Focal length: 4.5 mm (equivalent: 24 mm) Aperture: f/2.8 Focus: 1 m to ∞
Exposure Mode	Auto
Exposure Compensation	±3.0 (1/3 increments)
Metering Mode	Spot metering, Center-weighted metering
AE LOCK	Supported
Shutter Speed	1 ~ 1/8000
ISO Range	Video: 100 - 25600 Photo: 100 - 25600
Video Resolution	1920×1080@30fps
Video Format	MP4
Video subtitles	Supported
Photo Size	4056 x 3040
Photo Format	JPEG

Thermal Camera (Zenmuse H20T)

Sensor	Uncooled VOx Microbolometer

Lens	DFOV: 40.6° Focal length: 13.5 mm (equivalent: 58 mm) Aperture: f/1.0 Focus: 5 m to ∞
Digital Zoom	1x, 2x, 4x, 8x
Video Resolution	640×512 @ 30 Hz
Video Format	MP4
Image Resolution	640×512
Image Format	R-JPEG (16 bit)
Pixel Pitch	12 μm
Spectral Band	8-14 μm
Sensitivity (NETD)	≤50 mK @ f/1.0
Temperature Measurement Method	Spot Meter, Area Measurement
Scene Range	-40 °C to 150 °C (High Gain) -40 °C to 550 °C (Low Gain)
Temperature alert	Supported
FFC	Auto/ manual
Palette	White hot/Fulgurite/Iron Red/Hot Iron/Medical/Arctic/Rainbow 1/Rainbow 2/Tint/Black Hot

Laser Rangefinder

Wave length	905 nm
Measurement range	3-1200 m (to a vertical surface with ≥12m diameter and 20% reflection rate)
Measurement accuracy	± (0.2 m + D×0.15%) D is the distance to a vertical surface

Features

Hybrid Optical Zoom	23×（DFOV：4°，EQV：556.2mm）
Max. Zoom	200×（DFOV：0.5°，EQV：4800mm）
One Click Capture	One click to save the video or picture of 3 cameras (zoom, wide and thermal camera) simultaneously
Point to Aim	Double click on the wide/thermal camera view, then the system will automatically move the gimbal to focus o point of interest
High-Res Grid Photo	Frame an area of interest in wide camera view, and the zoom camera will automatically capture a set of 20 MP of the area. These images are stored together with an overview image that can be viewed in greater detail.
Night Scene	Supported (zoom camera)

Timestamp	Including GPS, date, and time

Storage

Supported SD Card	MicroSD card (Max capacity: 128 GB, UHS-1 Speed Grade 3 required)
Supported File Systems	FAT32 (≤ 32 GB), exFAT (> 32 GB)
Recommended Micro SD Cards	TOSHIBA EXCERIA PRO 32GB micro SD HC II SanDisk_Extreme PRO_32GB_3_A1_micro SD V30 HC I TOSHIBA EXCERIA PRO 64GB micro SD XC II SanDisk_Extreme PRO_64GB_3_A2_micro SD V30 XC I SAMSUNG_EVO_128GB_micro SD 3 XC I TOSHIBA EXCERIA M303E 32GB micro SD HC I TOSHIBA EXCERIA M303E 64GB micro SD XC I TOSHIBA EXCERIA M303E 64GB micro SD XC I TOSHIBA EXCERIA M303 128GB micro SD XC I SAMSUNG_EVO_64GB_micro SD 3 XC I

TELEDYNE

FLIR THERMAL STUDIO SUITE

SOFTWARE	THERMAL STUDIO STARTER	THERMAL STUDIO STANDARD	THERMAL STUDIO PRO
Subscription	Free	visit FLIR.com/Thermal-Studio-Suite for pricing	
File formats			
Image files	JPEGs, radiometric JPEGs		
Video files	MP4, CSQ, SEQ		
Export formats	PDF, XPS, JPG, ATR, HTML	PDF, XPS, JPG, ATR, CSV, HTML	PDF, XPS, JPG, ATR, CSV, AVI, HTML
Radiometric analysis			
View and edit radiometric images	Yes		
Spot, Box, Line, Ellipse/Circle	Yes		
Delta	—	Yes	
Formulas	—	Yes	
Measurement alarms	—	Humidity, Insulation	
Magic wand, Polygon, Polyline	—	—	Yes
Reporting			
Reporting with pre-defined templates	Yes		
Rapid Report	—	Yes	
Custom report templates	—	Up to five custom templates	Unlimited custom templates
Custom reporting with editor	—	Yes	
Custom logo in image	—	—	Yes
Manage routes with FLIR Route Creator Plugin*	—	—	Yes
Presentation features			
Image presentation modes	MSX®, thermal only, thermal fusion, blending, picture-in-picture, visual only		
Panorama	—	—	Yes
Image controls	MSX alignment, 90° rotation		MSX alignment, free rotation, resize, crop
Image annotations	Text, Voice		
Color distribution	Histogram equalization, signal linear, temperature linear	Histogram equalization, signal linear, temperature linear, Digital Detail Enhancement	
Custom image overlay	—	Yes	
Custom color palettes	—	—	Yes
Gas visualization	—	—	High sensitivity mode (HSM) and pixel binning
Streaming and recording			
View non-radiometric video	Yes		
Record non-radiometric video	Yes		
View radiometric video	Yes		
Edit radiometric video (SEQ and CSQ)	—	—	Yes
Record radiometric video	—	—	Yes
Segment video capabilities	—	—	Yes
Dual streaming (visual & IR)	—	—	Yes
Multi-image editing/batch processing			
Scale & units	—	Yes	
Image presentation	—	Palette, fusion, UltraMax®	Palette, fusion, fusion alignment, UltraMax, isotherm, alarm, clear isotherms, zoom factor, notes, color distribution, sketch, rotate
Measurements	—	Spots, clear all	Spots, Ellipses, Rectangles, Lines, Delta, clear all
Parameters	—	Emissivity, distance	Emissivity, reflected temperature, reference temperature, distance, atmospheric temperature, external optics temperature, external optics transmission, relative humidity
Output	—	Radiometric JPG	Radiometric JPG, JPG, CSV, AVI, Map, Graphy
Plugin support (sold separately)			
FLIR Route Creator	—	—	Yes
FLIR Si-Series Plugin	Yes	Yes	Yes
System Compatibility			
Compatible FLIR products	All cameras that generate images in radiometric JPG format (including A-, B-, C-, K-, T-, E-, GF-, i-, P6-, FLIR One series), and Si124 Acoustic Imaging Cameras (Si124, Si124-LD, Si124-PD)		
Compatible cameras with embedded FLIR Inspection Route	FLIR E54, E76, E86, E96, GF77 and any T-Series camera purchased after October 8, 2020		
FLIR Ignite™	Access images uploaded to FLIR Ignite cloud from Thermal Studio using Ignite Sync		
System requirements	Windows 8 or later / Thermal Studio 1.7 and later versions supports 64-bit only / RAM: Minimum 4 GB / Disk space: Minimum 250 MB		

Specifications are subject to change. For the most up-to-date specifications, please visit teledyneflir.com.

TELEDYNE

FAST, EFFICIENT THERMAL ANALYSIS AND REPORTING

THE FLIR THERMAL STUDIO SUITE

This state-of-the-art analysis software is designed to help users manage thousands of thermal images and videos and quickly produce professional reports. Compatible with files from handheld thermal cameras, unmanned aircraft systems (UAS), acoustic imaging cameras, and optical gas imaging (OGI) cameras, this software offers the features needed to streamline workflow and increase productivity.

THREE TIERS, ONE POWERFUL SOFTWARE

FLIR offers three software tiers providing the capabilities users need at a range of affordable prices. All three versions can directly access the FLIR Ignite library via Wi-Fi for downloading stored images from the cloud.†

FLIR THERMAL STUDIO STARTER

- Free license
- View and edit radiometric images
- Quick reporting with pre-defined templates

FLIR THERMAL STUDIO STANDARD

- 1-year or perpetual subscription
- Customize reports
- Advanced measurement and image analysis
- Basic multi-image editing (batch processing)

FLIR THERMAL STUDIO PRO

- 1-year or perpetual subscription
- Full range of advanced analysis and reporting functionality
- View, stream, and record radiometric video (includes dual streaming)
- Batch processing with all image and measurement controls
- Compatible with FLIR Route Creator plugin (optional) for building and downloading inspection plans

FLIR THERMAL STUDIO PLUGINS

FLIR THERMAL STUDIO PLUGINS

Complete your inspections efficiently and reduce reporting time by 50% with the FLIR Route Creator plugin for FLIR Thermal Studio Pro. This plugin allows you to build an inspection path for every location survey that you can either print or download and run from a thermal camera that has FLIR Inspection Route enabled.* Inspection Route directs you through the pre-planned survey so you can acquire temperature data and thermal images in a logical sequence. This helps automate data management and allows you to easily maintain historical records for improved predictive maintenance.

Once you've completed an inspection, you can upload images to the FLIR Ignite cloud† or import images, data, and notes directly into your report templates, cutting your reporting time in half.

*Exx-Series and T-Series cameras purchased prior to October 8, 2020 will require the addition of FLIR Inspection Route. Camera option is included on E54, E76, E86, E96, and all new T-Series cameras.

† Required FLIR Ignite firmware available.

FLIR SI-SERIES PLUGIN

The FLIR Si-Series Plugin allows you to import acoustic images from FLIR Si124 cameras to FLIR Thermal Studio, edit and analyze them, and create advanced reports. With the plugin you'll have support for automatic fault classification, severity indication, recommended action for utility inspections, and estimation of leak volume and cost savings for air leaks. Combine acoustic images with thermal imaging in the same report.

The FLIR Si-Series Plugin is available as a perpetual license and is compatible with all versions of FLIR Thermal Studio desktop software (Starter, Standard, and Pro).

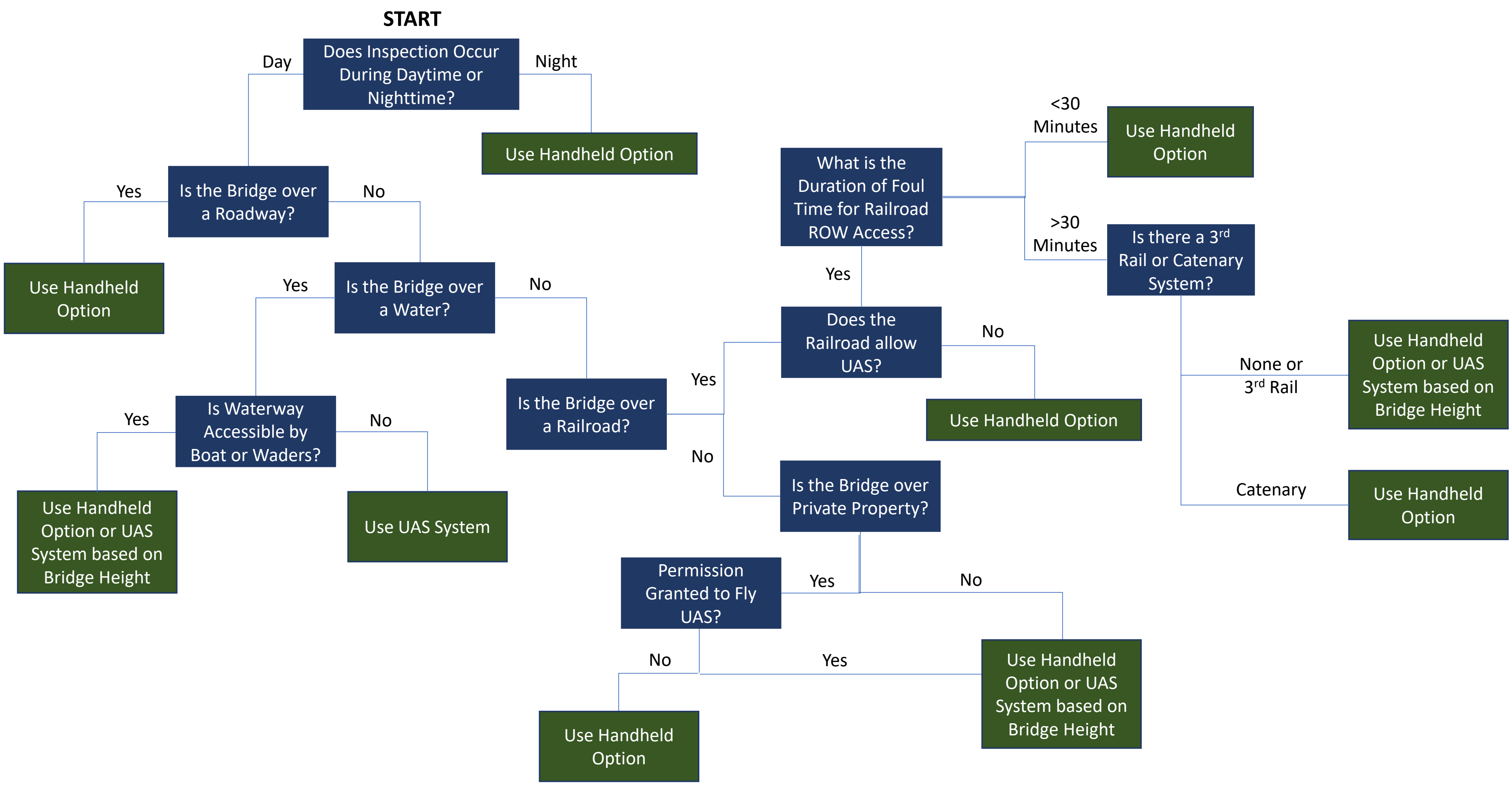
For more information please visit:

www.flir.com/si-series-plugin

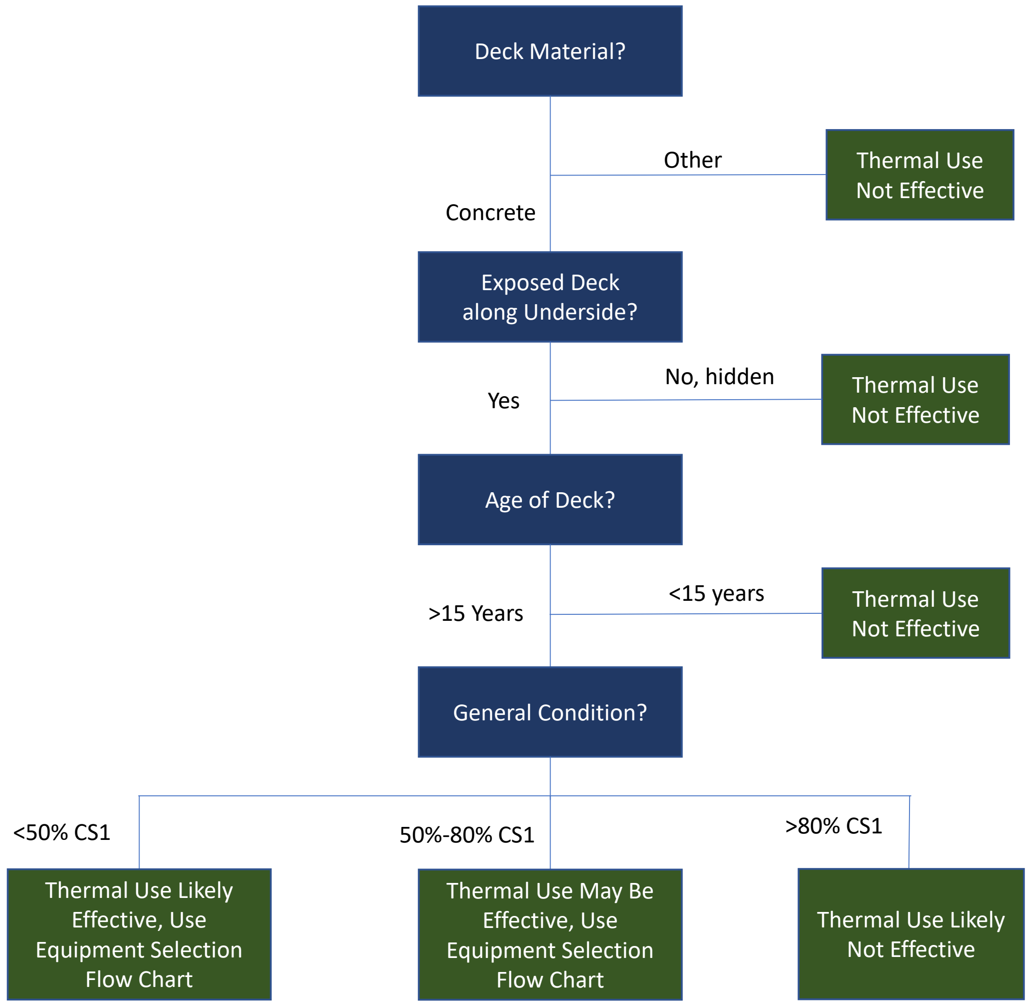
Appendix B

Flow Charts

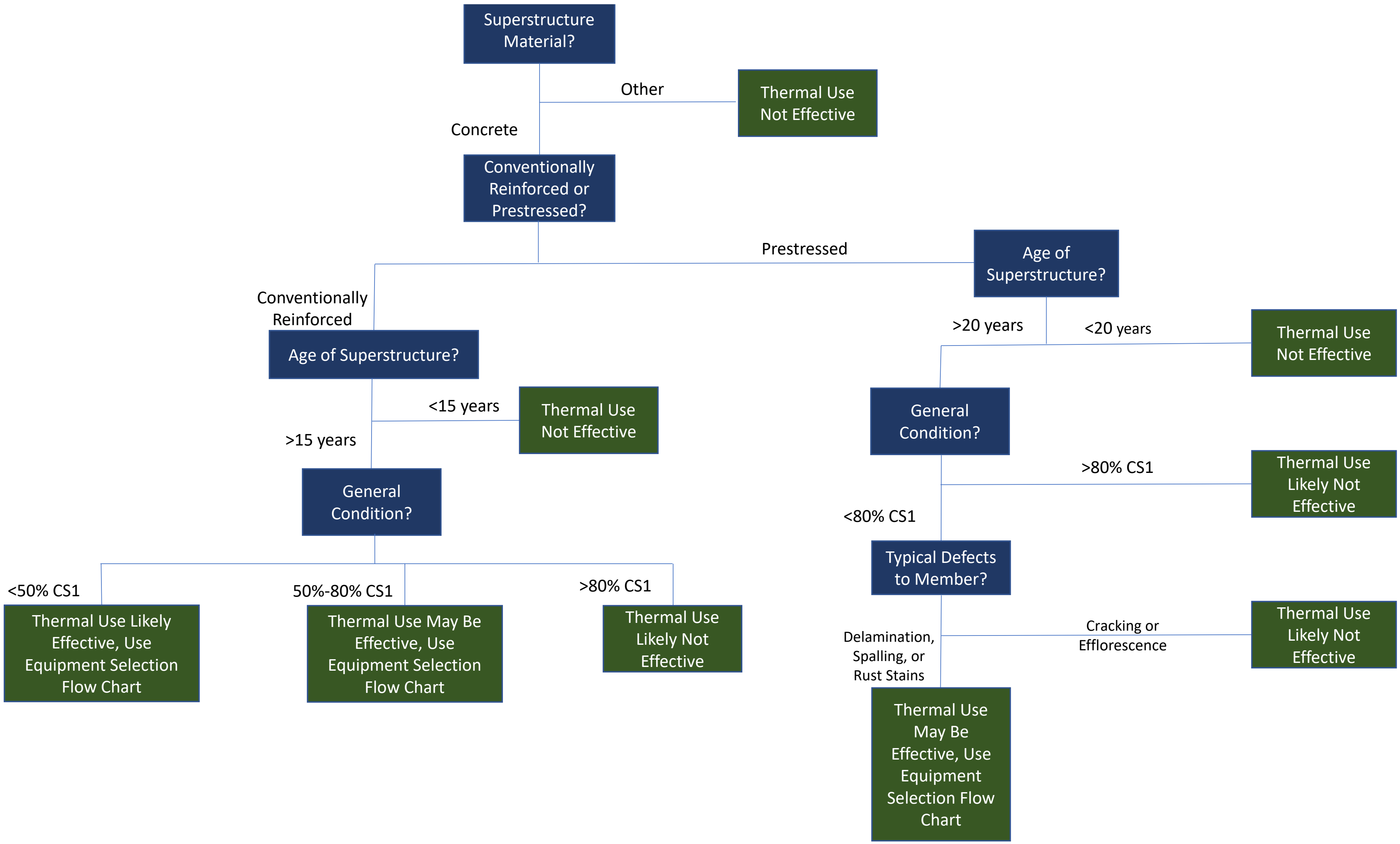
Flow Chart to Determine Type of Equipment



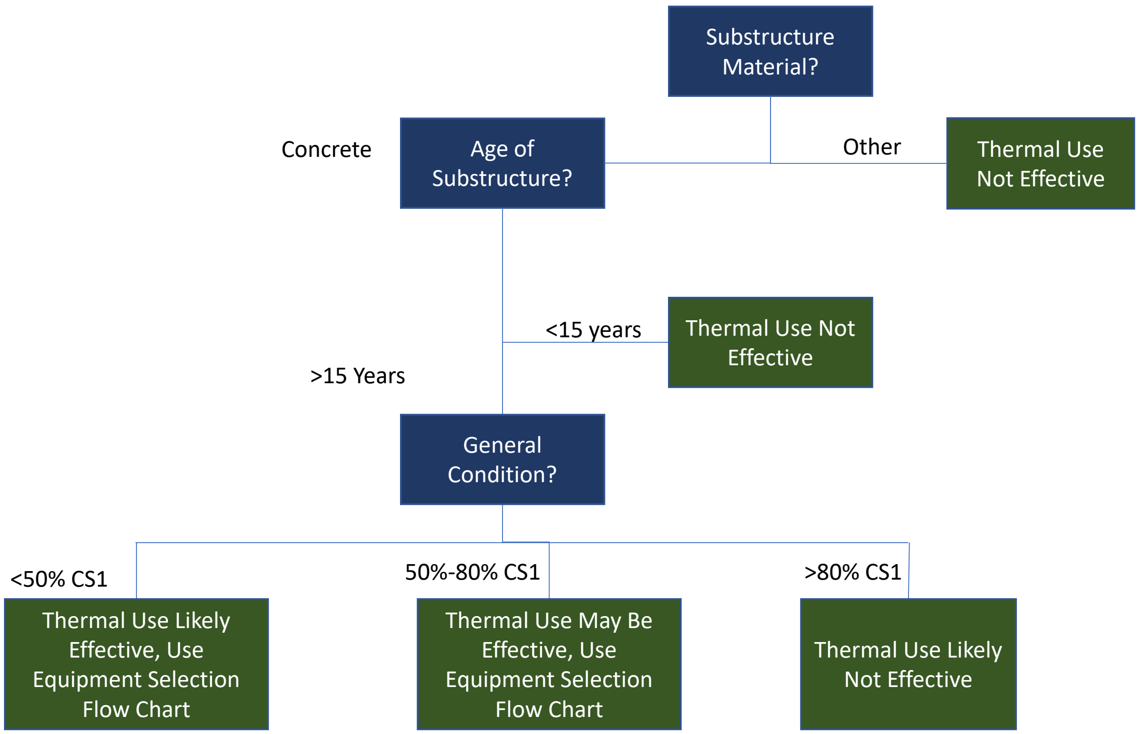
Flow Chart to Determine Effectiveness for Underside of Bridge Decks



Flow Chart to Determine Effectiveness for Superstructure Elements



Flow Chart to Determine Effectiveness for Substructure Elements



Appendix C

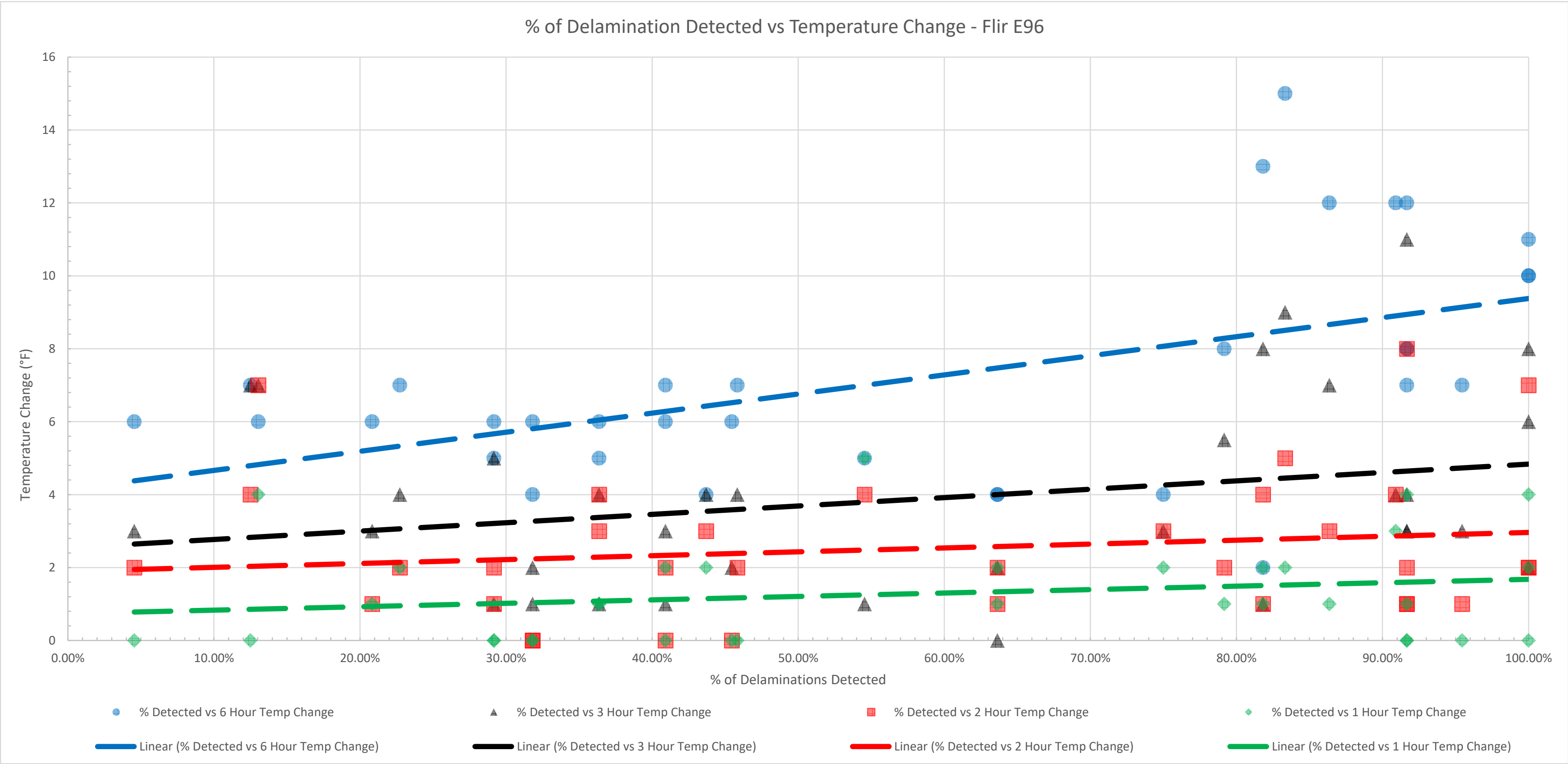
Temperature and Weather Condition Summary Charts

Flir E96 Detection Rates, Temperature Change, and Atmospheric Conditions

Info		Date and Time				Temperature Changes									Atmospheric Conditions				Detection Rates	
BIN	Camera	Data Set	Date	Start Time	End Time	Temp at Time of Testing (°F)	Temp 6 Hrs Prior (°F)	Δ Temp 6 Hrs (°F)	Temp 3 Hrs Prior (°F)	Δ Temp 3 Hrs (°F)	Temp 2 Hr Prior (°F)	Δ Temp 2 Hrs (°F)	Temp 1 Hr Prior (°F)	Δ Temp 1 Hr (°F)	Dew Point (°F)	Humidity (%)	Wind Speed (mph)	Last Rainfall	% Detected	% Not Detected
4E5	Flir E96	**1**	9/13/2021	1:40 PM	2:02 PM	82	70	12	78	4	78	4	79	3	57	45	9	6 hours prior	90.91%	9.09%
4E5	Flir E96	**2**	9/14/2021	9:47 AM	10:05 AM	72	65	7	68	4	70	2	70	2	55	55	8	26 hours prior	22.73%	77.27%
4E5	Flir E96	**3**	9/14/2021	11:23 AM	11:33 AM	72	66	6	70	2	72	0	72	0	55	53	9	30 hours prior	31.82%	68.18%
4E5	Flir E96	**4**	9/15/2021	10:38 AM	10:46 AM	83	71	12	76	7	80	3	82	1	71	67	13	2 days prior	86.36%	13.64%
4E5	Flir E96	**5**	9/15/2021	11:49 AM	12:11 PM	84	71	13	76	8	80	4	82	2	71	67	13	2 days prior	81.82%	18.18%
4E5	Flir E96	**6**	9/15/2021	2:43 PM	3:03 PM	84	80	4	84	0	85	1	85	1	69	61	18	2 days prior	63.64%	36.36%
4E5	Flir E96	**7**	9/16/2021	8:55 AM	9:03 AM	70	74	4	68	2	68	2	68	2	64	81	7	1 hour prior	63.64%	36.36%
4E5	Flir E96	**8**	9/16/2021	10:13 AM	10:20 AM	65	70	5	64	1	69	4	70	5	65	84	7	2 hours prior	54.55%	45.45%
4E5	Flir E96	**9**	9/18/2021	12:10 PM	12:19 PM	72	66	6	69	3	70	2	72	0	65	78	5	2 days prior	4.55%	95.45%
4E5	Flir E96	**10**	9/18/2021	1:32 PM	1:41 PM	72	66	6	70	2	72	0	72	0	65	79	6	2 days prior	45.45%	54.55%
4E5	Flir E96	**11**	9/18/2021	2:16 PM	2:23 PM	72	68	4	73	1	72	0	72	0	65	78	8	2 days prior	31.82%	68.18%
4E5	Flir E96	**12**	9/19/2021	7:49 PM	7:55 PM	64	71	7	67	3	65	1	64	0	55	72	5	16 hours prior	95.45%	4.55%
4E5	Flir E96	**13**	9/22/2021	1:02 PM	1:10 PM	76	70	6	77	1	76	0	78	2	67	74	20	3 days prior	40.91%	59.09%
4E5	Flir E96	**14**	9/22/2021	2:08 PM	2:14 PM	77	72	5	76	1	80	3	76	1	68	74	9	3 days prior	36.36%	63.64%
4E5	Flir E96	**15**	9/23/2021	1:02 PM	1:09 PM	76	70	6	80	4	80	4	77	1	67	74	7	Rain during data collection	36.36%	63.64%
4E5	Flir E96	**16**	9/23/2021	7:47 PM	7:55 PM	70	81	11	76	6	72	2	72	2	66	87	13	7 hours prior	100.00%	0.00%
4E5	Flir E96	**17**	9/23/2021	8:45 PM	8:50 PM	70	80	10	72	2	72	2	70	0	66	87	10	8 hours prior	100.00%	0.00%
4E5	Flir E96	**18**	9/24/2021	9:52 AM	10:04 AM	78	71	7	75	3	76	2	78	0	69	74	14	20 hours prior	40.91%	59.09%
4E5	Flir E96	**19**	9/25/2021	10:24 AM	10:32 AM	73	67	6	66	7	66	7	69	4	52	48	5	2 days prior	13.04%	86.96%
4E5	Flir E96	**20**	9/25/2021	11:06 AM	11:12 AM	73	66	7	66	7	69	4	73	0	50	44	8	2 days prior	12.50%	87.50%
4E5	Flir E96	**21**	9/25/2021	6:52 PM	6:59 PM	65	73	8	68	3	66	1	65	0	61	87	7	Rain during data collection	91.67%	8.33%
4E5	Flir E96	**22**	9/25/2021	7:34 PM	7:51 PM	65	72	7	68	3	66	1	65	0	61	87	7	Rain during data collection	91.67%	8.33%
4E5	Flir E96	**23**	9/26/2021	7:59 PM	8:06 AM	67	75	8	71	4	69	2	68	1	46	47	13	13 hours prior	91.67%	8.33%
4E5	Flir E96	**24**	9/30/2021	9:45 AM	9:51 AM	60	55	5	55	5	58	2	60	0	43	53	12	2 days prior	29.17%	70.83%
4E5	Flir E96	**25**	9/30/2021	10:38 AM	10:45 AM	61	55	6	58	3	60	1	60	1	42	50	10	2 days prior	20.83%	79.17%
4E5	Flir E96	**26**	9/30/2021	11:43 AM	11:49 AM	61	55	6	60	1	60	1	61	0	42	50	8	2 days prior	29.17%	70.83%
4E5	Flir E96	**27**	9/30/2021	6:20 PM	6:27 PM	60	62	2	61	1	61	1	61	1	43	55	10	2 days prior	81.82%	18.18%
4E5	Flir E96	**28**	9/30/2021	7:06 PM	7:14 PM	58	62	4	61	3	61	3	60	2	44	59	9	2 days prior	75.00%	25.00%
4E5	Flir E96	**29**	10/1/2021	9:36 AM	9:51 AM	63	51	12	52	11	55	8	59	4	45	50	15	3 days prior	91.67%	8.33%
4E5	Flir E96	**30**	10/1/2021	10:59 AM	11:05 AM	66	51	15	57	9	61	5	64	2	44	45	10	3 days prior	83.33%	16.67%
4E5	Flir E96	**31**	10/6/2021	9:24 AM	9:45 AM	64	56	8	59	5.5	62	2	63	1	52	64	0	30 hours prior	79.17%	20.83%
4E5	Flir E96	**32**	10/7/2021	1:38 PM	1:45 PM	72	65	7	68	4	70	2	72	0	57	59	6	2 days prior	45.83%	54.17%
4EU	Flir E96	-	9/23/2021	7:35 AM	8:14 AM	72	68	4	68	4	69	3	70	2	67	84	8	2 days prior	43.70%	56.30%
4EU	Flir E96	-	9/23/2021	9:18 AM	9:38 AM	78	68	10	70	8	71	7	74	4	67	79	12	2 days prior	100.00%	0.00%

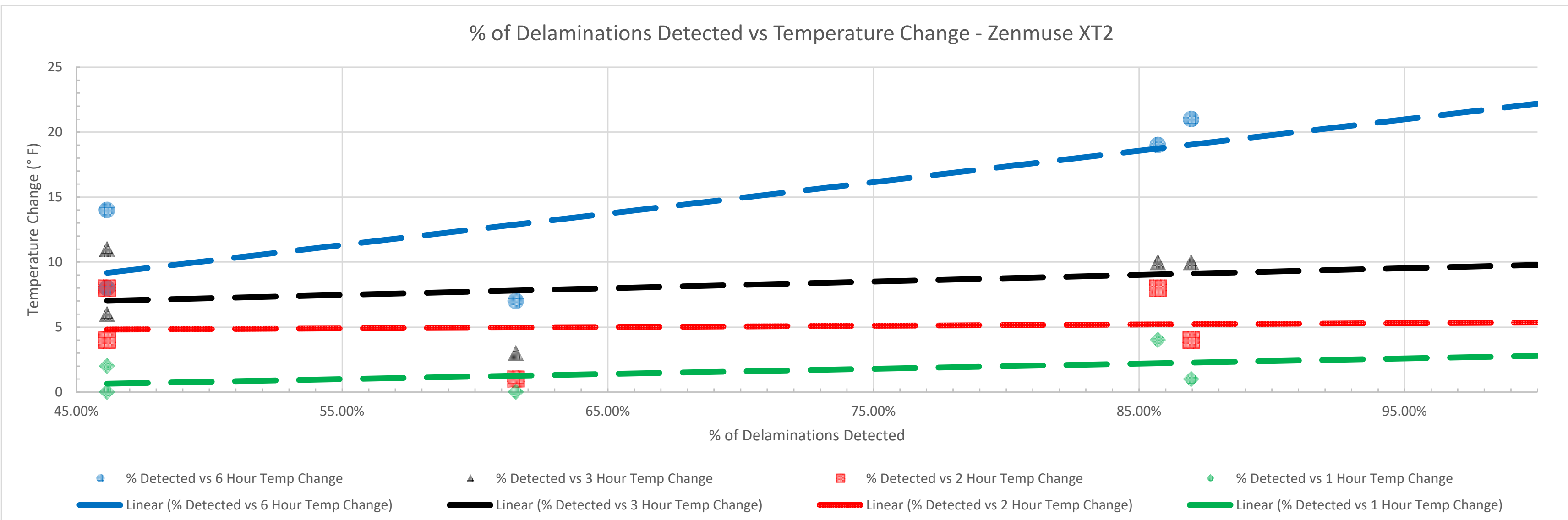
Key:

- **> 80%** (dark green)
- **80%-60%** (light green)
- **60%-50%** (yellow)
- **50%-30%** (orange)
- **< 30%** (red)


% of Delamination Detected vs Temperature Change - Flir E96
Temperature Change (°F)
16
14
12
10
8
6
4
2
0
0.00%
10.00%
20.00%
30.00%
40.00%
50.00%
60.00%
70.00%
80.00%
90.00%
100.00%
% of Delaminations Detected
% Detected vs 6 Hour Temp Change
% Detected vs 3 Hour Temp Change
% Detected vs 2 Hour Temp Change
% Detected vs 1 Hour Temp Change
Linear (% Detected vs 6 Hour Temp Change)
Linear (% Detected vs 3 Hour Temp Change)
Linear (% Detected vs 2 Hour Temp Change)
Linear (% Detected vs 1 Hour Temp Change)

Zenmuse XT2 Detection Rates, Temperature Change, and Atmospheric Conditions																			
Info		Date and Time			Temperature Changes									Atmospheric Conditions				Detection Rates	
BIN	Camera	Date	Start Time	End Time	Temp at Time of Testing (°F)	Temp 6 Hrs Prior (°F)	Δ Temp 6 Hrs (°F)	Temp 3 Hrs Prior (°F)	Δ Temp 3 Hrs (°F)	Temp 2 Hr Prior (°F)	Δ Temp 2 Hrs (°F)	Temp 1 Hr Prior (°F)	Δ Temp 1 Hr (°F)	Dew Point (°F)	Humidity (%)	Wind Speed (mph)	Last Rainfall	% Detected	% Not Detected
4RT	DJI XT2	10/19/2021	10:36 AM	11:26 AM	55	47	8	49	6	51	4	55	0	36	47	17	14 days prior	46.15%	53.85%
4RT	DJI XT2	10/22/2021	11:39 AM	12:00 PM	70	63	7	67	3	69	1	70	0	49	47	15	17 days prior	61.54%	38.46%
4RT	DJI XT2	1/19/2022	10:23 AM	10:40 AM	35	21	14	24	11	27	8	33	2	23	57	17	1 day prior	46.15%	53.85%
114	DJI XT2	10/20/2021	10:58 AM	12:01 PM	71	52	19	61	10	63	8	67	4	51	49	5	3 days prior	85.71%	14.29%
114	DJI XT2	10/21/2021	12:12 PM	12:29 PM	74	53	21	64	10	70	4	73	1	50	43	12	4 days prior	86.96%	13.04%

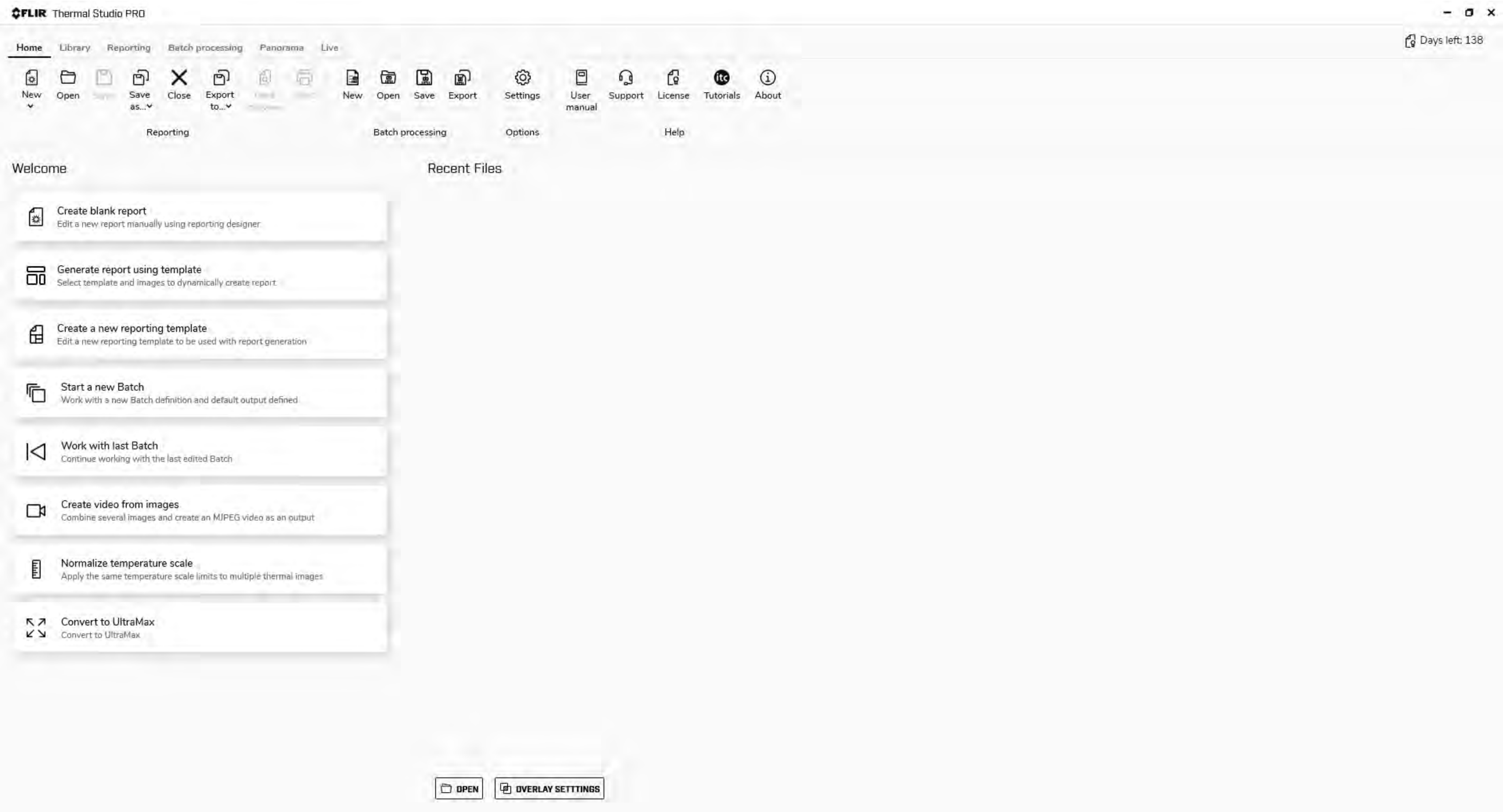
Key:
- **> 80%**
- **80%-60%**
- **60%-50%**
- **50%-30%**
- **< 30%**



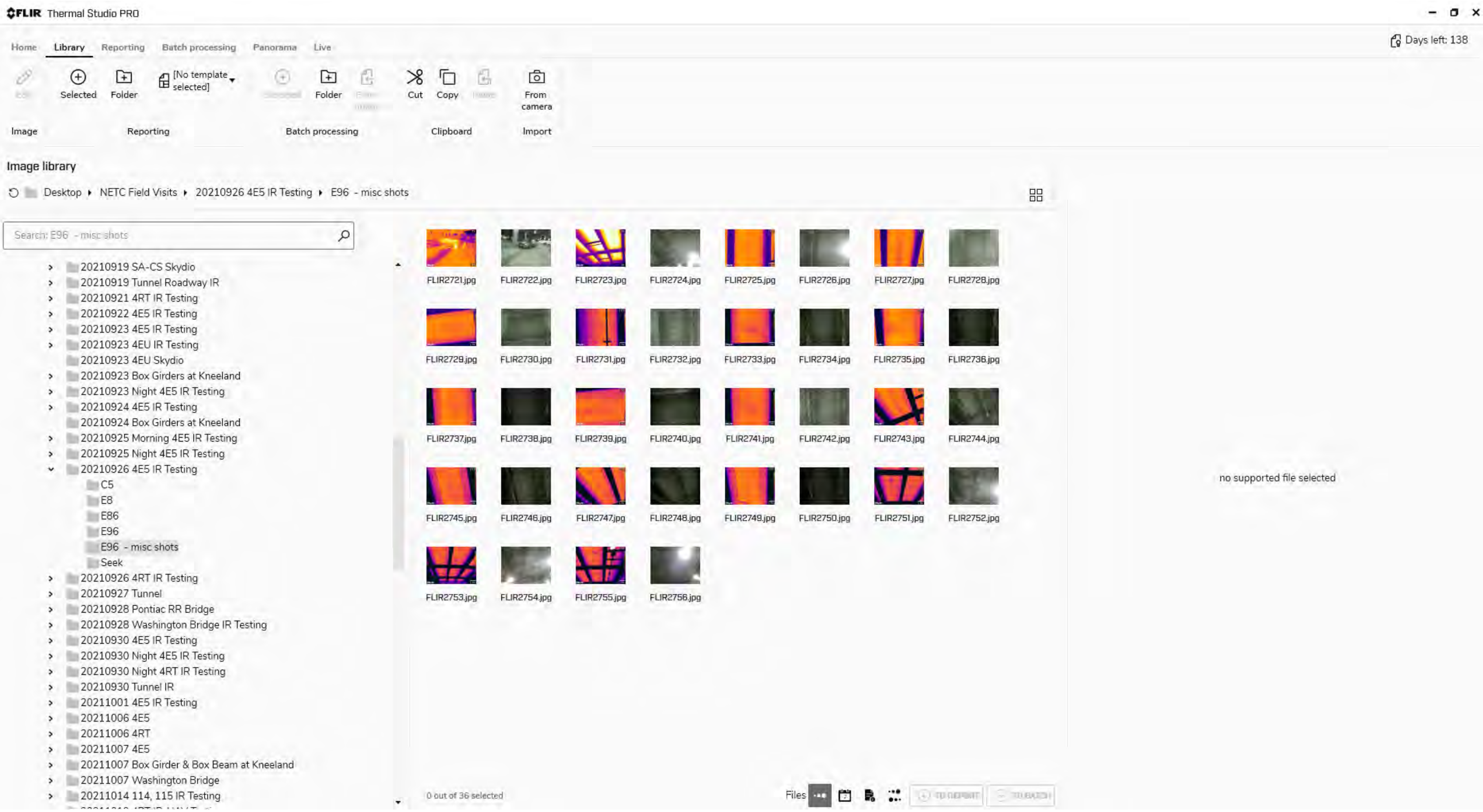
Appendix D

Overview of Flir Thermal Studio

Home


FLIR Thermal Studio PRO
Days left: 138
Home
Library
Reporting
Batch processing
Panorama
Live
New
Open
Save as...
Close
Export to...
New
Open
Save
Export
Settings
User manual
Support
License
Tutorials
About
Reporting
Batch processing
Options
Help
Welcome
Recent Files
Create blank report
Edit a new report manually using reporting designer
Generate report using template
Select template and images to dynamically create report
Create a new reporting template
Edit a new reporting template to be used with report generation
Start a new Batch
Work with a new Batch definition and default output defined
Work with last Batch
Continue working with the last edited Batch
Create video from images
Combine several images and create an MJPEG video as an output
Normalize temperature scale
Apply the same temperature scale limits to multiple thermal images
Convert to UltraMax
Convert to UltraMax
OPEN
OVERLAY SETTINGS

Library


FLIR Thermal Studio PRO
Home
Library
Reporting
Batch processing
Panorama
Live
Days left: 138
Selected
Folder
[No template selected]
Folder
Cut
Copy
From camera
Image
Reporting
Batch processing
Clipboard
Import
Image library
Desktop
NETC Field Visits
20210926 4E5 IR Testing
E96 - misc shots
Search: E96 - misc shots
20210919 SA-CS Skydio
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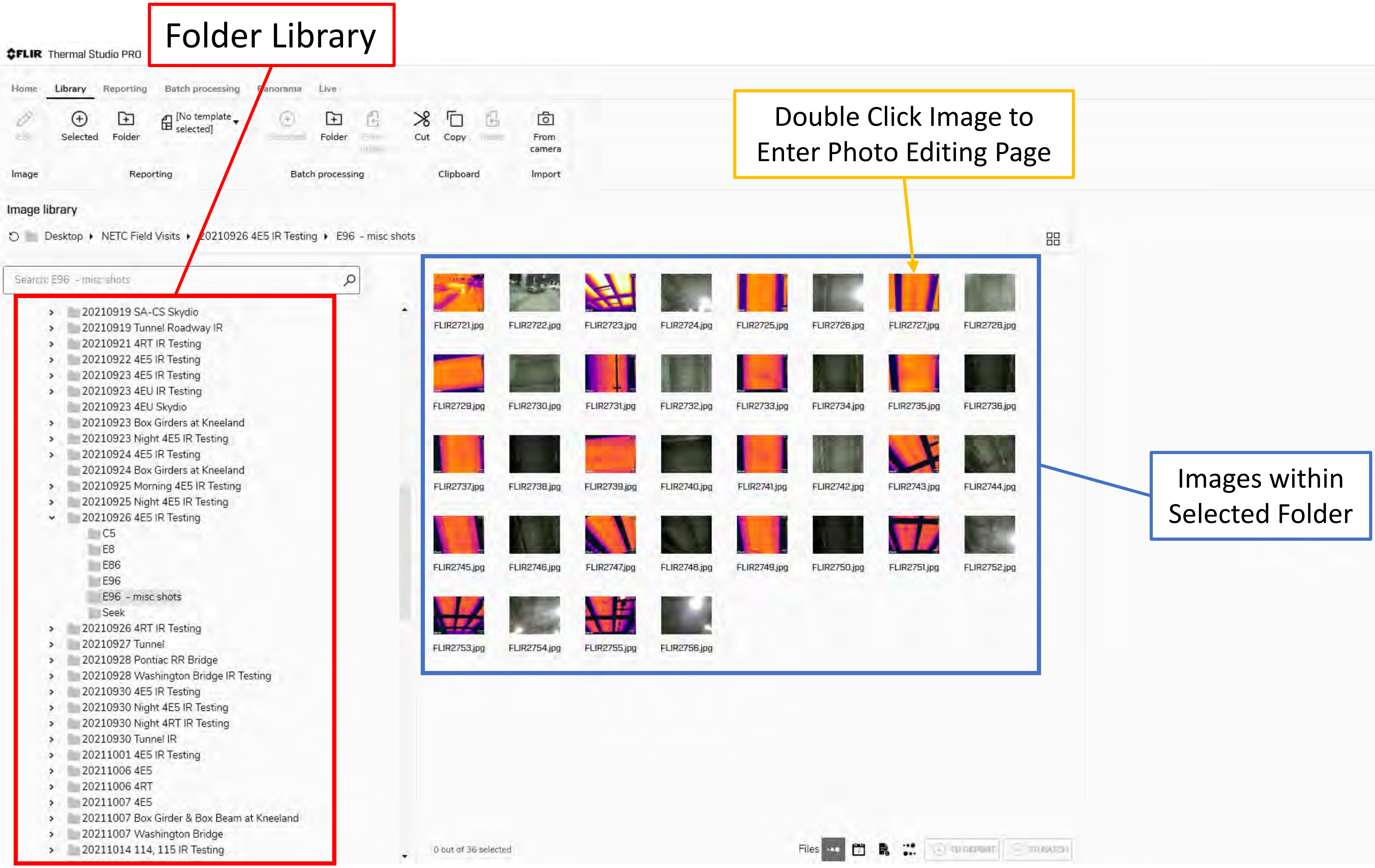
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Photo Editing

Photo Editing

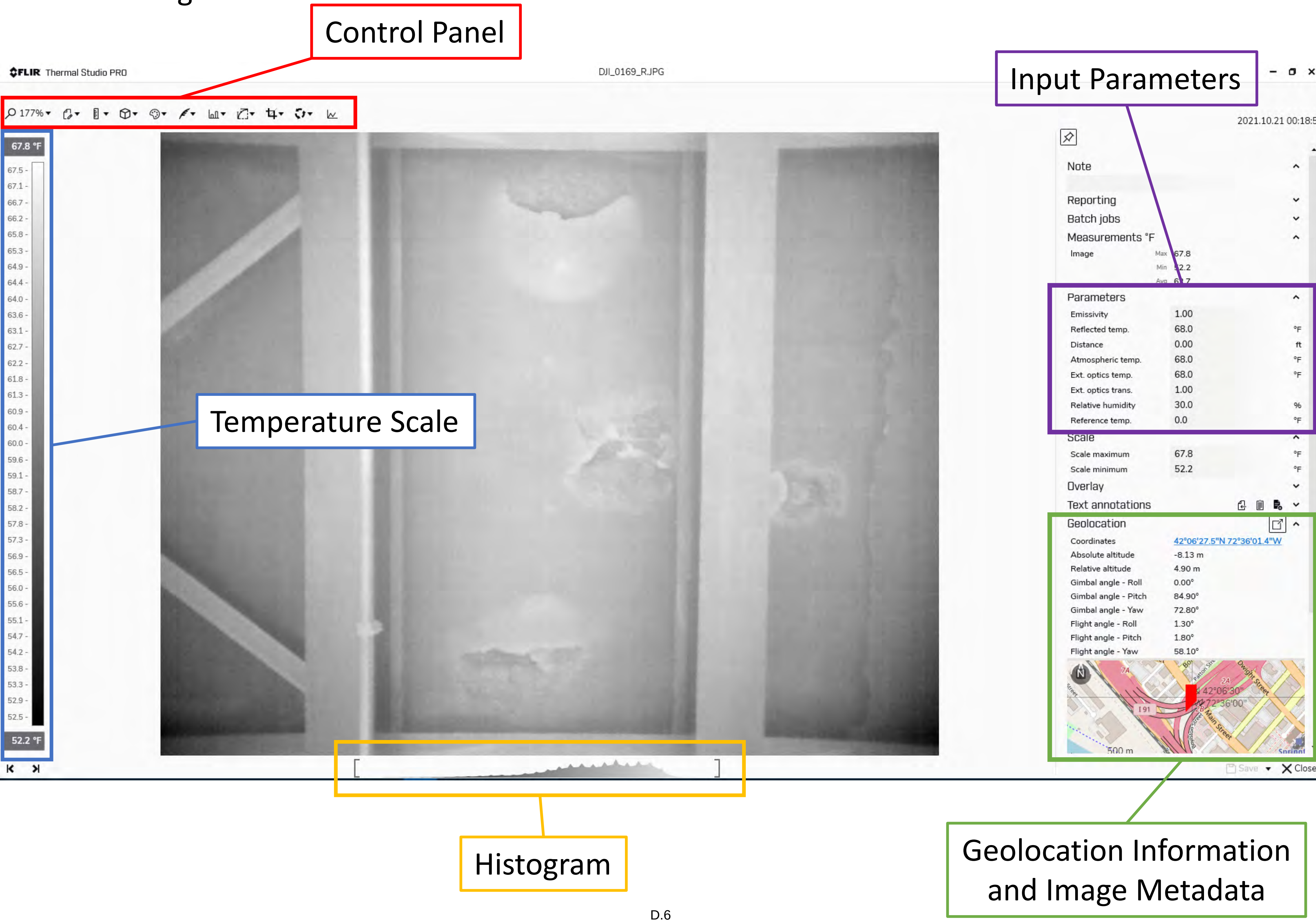


Photo Editing – Control Panel

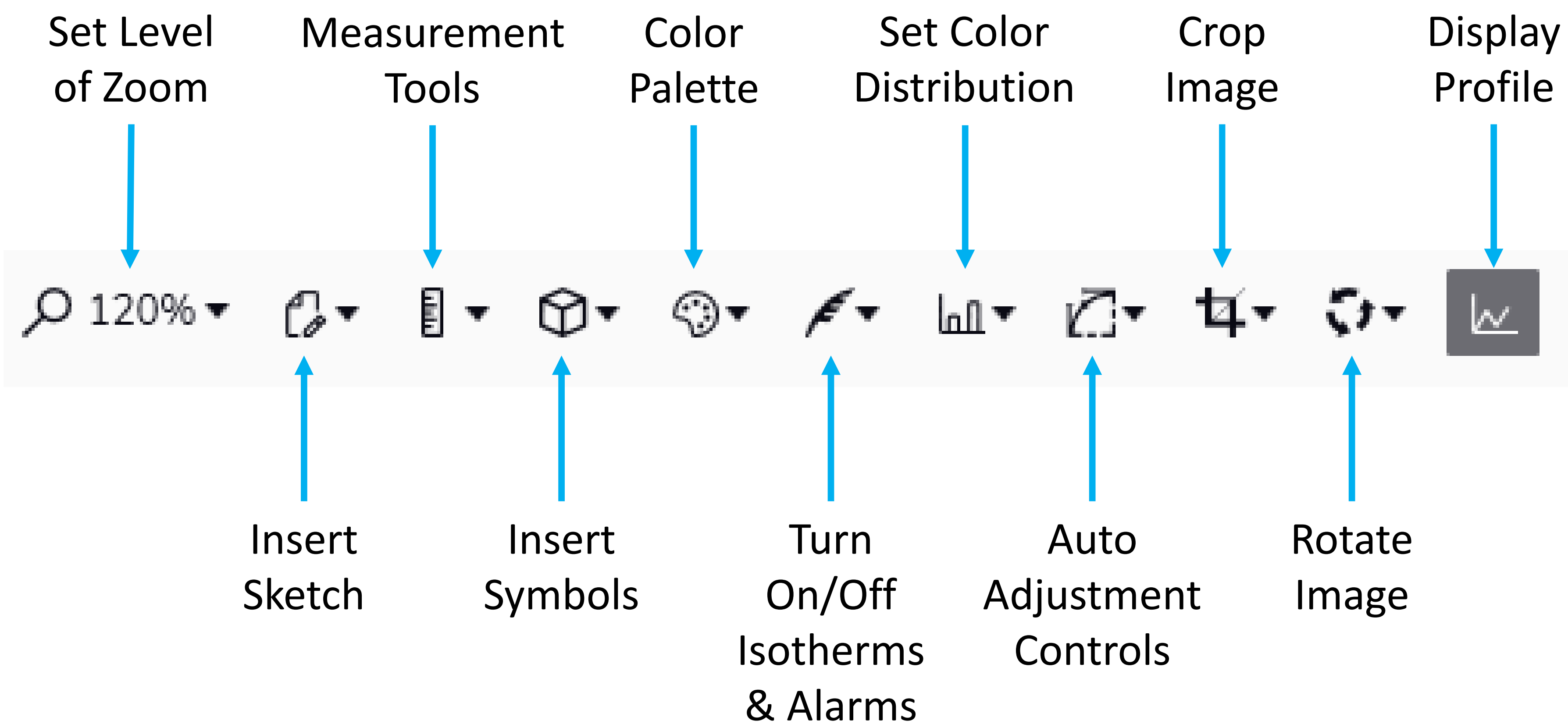
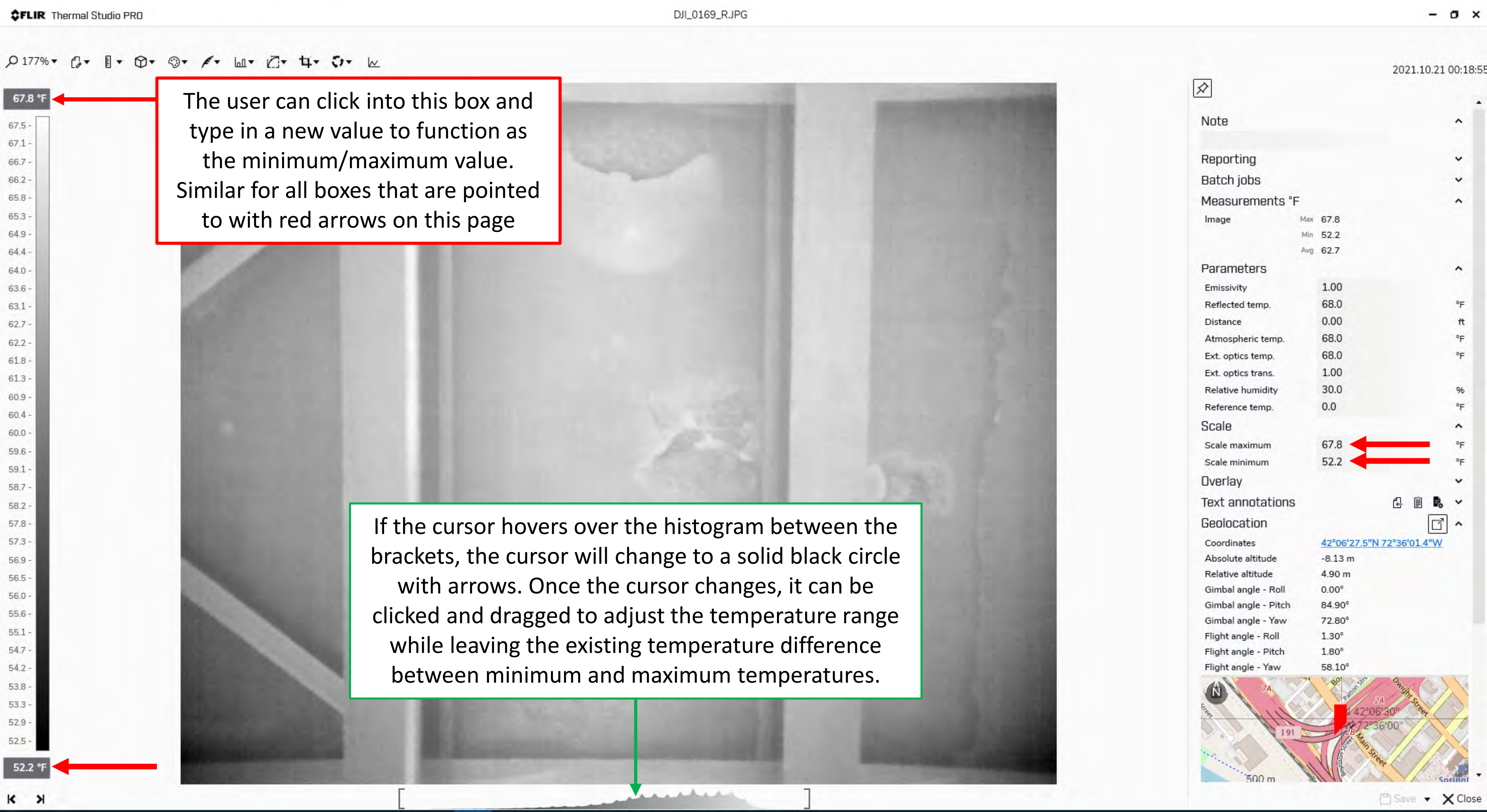


Photo Editing – Adjusting Temperature Values



The user can click into this box and type in a new value to function as the minimum/maximum value. Similar for all boxes that are pointed to with red arrows on this page

If the cursor hovers over the histogram between the brackets, the cursor will change to a solid black circle with arrows. Once the cursor changes, it can be clicked and dragged to adjust the temperature range while leaving the existing temperature difference between minimum and maximum temperatures.

Hover cursor over bracket, the cursor will change to a horizontal line with arrows on either end. One the cursor changes, it can be clicked and dragged to adjust the minimum/maximum temperature values

Photo Editing

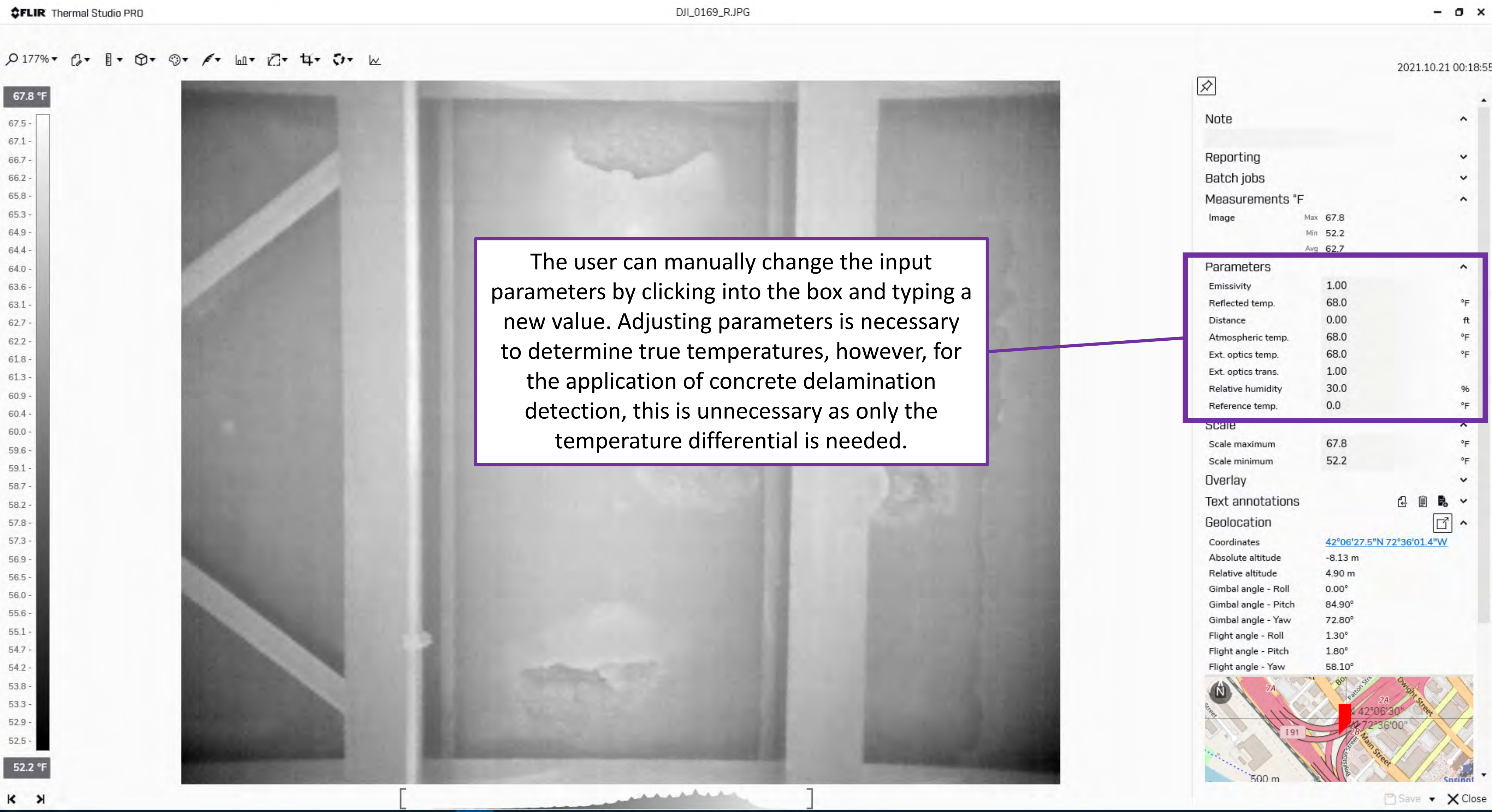


Photo Editing