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UAV Based Inspections for Highway Bridge and Structural Condition Monitoring and Inspection works

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Bridges play a key role in supporting the transportation network in the United States. The 2021 infrastructure report card prepared by ASCE highlighted that more than 40% of bridges in the U.S. are over 50 years old. To address these challenges, highway agencies are exploring innovative technologies to conduct inspections and realize benefits in terms of access, cost, and safety. Federal and state DOTs have conducted several studies on the application of uncrewed aerial vehicles (UAVs) for bridge health monitoring. In this current research, UAVs were used to develop a workflow for conducting 360° inspections of several different bridges in Alaska. The locations of the aerial images during the inspections were also pictographically represented to provide a holistic idea of the developed workflow for the highway agencies and practitioners. Three-dimensional models representing the actual conditions of the bridge were generated and used for comparing the bridge condition assessments with traditional inspection reports. The applicability and recommendation scale for the use of UAVs for different bridge inspections was provided. The approach demonstrated in this study is expected to result in more than 90% savings in storage requirements and contribute to an increase in the application of UAVs for conducting 360° bridge inspections across the U.S.

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yd	yards	0.914		m	m	meters	1.09	yards	yd
mi	Miles (statute)	1.61		km	km	kilometers	0.621	Miles (statute)	mi
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ac	acres	0.4046	hectares	ha					
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oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME					VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft^3	cubic feet	0.0283	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
Note: Volumes greater than 1000 L shall be shown in m^3									
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C	°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
		ILLUMINATION					ILLUMINATION		
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2	cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

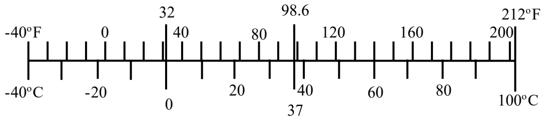

Table of Contents

List of Figures

List of Tables

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Executive Summary

Bridges play a key role in supporting the transportation network in the United States. The 2021 infrastructure report card prepared by ASCE highlighted that more than 40% of bridges in the U.S. are over 50 years old. Some of these bridges are classified as structurally deficient, even though they are safe to travel. To address these challenges, highway agencies are exploring innovative technologies to conduct mandatory annual inspections and realize benefits in terms of access, cost, and safety. Federal and state DOT agencies have conducted several studies on the application of uncrewed aerial vehicles (UAVs) for bridge health monitoring as a part of annual condition assessments. Many previous studies have accomplished bridge deck inspections using infrared, optical images, and three-dimensional (3D) models. The 3D mapping of a bridge deck is similar to that of horizontal planar surfaces such as pavements. However, not many studies have reported the three-dimensional reconstruction of the under-span of a bridge and its limitations. The 360° bridge models are essentially digital replicas depicting the existing conditions of bridges. They can provide visuals of the super- and sub-structure elements of a bridge. Moreover, they also offer the benefit of associating images with the bridge elements in the 360° models.

In the current study, the researchers collaborated with the bridge division of the Alaska Department of Transportation and Public Facilities (Alaska DOT&PF) to understand the challenges and identify the best practices for using UAVs to conduct 360° inspections of bridge infrastructure assets in Alaska. The current study demonstrated the use of UAVs for conducting 360° inspections of multiple bridges using optical and infrared imagery. During the first two years of the project, UAV-based data collection was performed at eleven bridges. In addition, two buildings and a tower were also inspected during the first and second years of inspection, respectively. Different bridges were selected to represent a wide range of bridge types and conditions and develop a generalized workflow for conducting 360° bridge inspections. The workflow for 360° bridge inspection was developed while performing the Year I bridge inspections. The developed workflow was refined based on the project technical team's input and demonstrated during the Year II bridge inspections. Optical images were used to build 3D models of the bridges for quantitative inspection and infrared images were also used to conduct a qualitative inspection of bridges.

The locations of the aerial images captured during the inspections were also pictographically represented to provide a holistic idea of the 360° bridge inspection workflow for the highway agencies and practitioners. Three-dimensional models representing the actual conditions of the bridge were generated and used for comparing the bridge condition assessments with traditional inspection reports. The importance of thermal loading in depicting distress conditions was highlighted in these inspections. The 360° digital model was also able to remotely provide information about the bent elements of the steel truss, which reduces the need for using special crew lift equipment to spot them on a steel truss bridge and any associated traffic delay due to lane closures. Individual aerial images of bridges, especially under-bridge spans, might look the same, and can be difficult to differentiate the location. Poor GPS conditions also contribute to this issue. Hence, 3D models provide context to the images and serve as a repository of inspection images. As reported by previous literature, orthorectified and stitched images being overlaid on the bridge plans were found to help provide scaled views of the bridge elements and identify the spalled areas, rusted areas, cracking extent, and other distress. Further, the practice of using orthomosaics of all bridge faces instead of 3D models was found to be effective in reducing the data storage requirements of the bridges considered in this study by more than 90%. Simultaneously using multiple RPICs and multiple drones can be explored to reduce the data collection time, however, the objectives and planning of operations need to be discussed before coordinating the collection of complementary data.

During the technology transfer workshop conducted in Year III, the bridge division personnel of Alaska DOT&PF was provided a detailed seminar on the developed workflow. Subsequently, they used UAVs to conduct a 360° inspection of a bridge that experienced flooding due to a glacier melt in Juneau. Multiple drone pilots and visual observers were split into groups to simultaneously conduct data collection of bridge elements in different stages. The workshop was successful in providing the details of the workflow and a hands-on experience for conducting 360° bridge inspections using UAVs.

CHAPTER 1 - INTRODUCTION

Problem Statement

Bridges are designed and constructed with the intent of providing a safe and durable structure for a long service life varying between 50 to 75 years. Alaska Department of Transportation and Public Facilities (Alaska DOT&PF) adheres to 23 CFR 625.4 specifying the most current edition of AASHTO LRFD and section 7.1 of Alaska Bridge and Structures Manual as the minimum design standards for all new bridges in the state of Alaska. Still, many structural elements of the bridge deteriorate over time due to various reasons including the surrounding environment, loading conditions, and weather events. Therefore, systematic periodic bridge inspection is essential to evaluate the condition and functionality of the in-service bridges, to detect any structural problems, and to ensure the design life of bridges.

The National Bridge Inspection Standards (NBIS) (23 CFR Part 650, Subpart C) comprises a nationwide bridge inspection, load rating, and inventory program. The Federal Highway Administration has followed regulations to establish the specific criteria that each state department of transportation must meet; basically, state Departments of Transportation (DOTs) agencies are responsible for proper NBIS safety inspection and evaluation of all public bridges located within the geographic boundaries of the state but not within federal lands.

Alaska has over one thousand bridges that require recurring inspections to comply with 23 CFR 650.311. The current practice for routine level inspection, conducted every 24 months, utilizes bridge inspectors from the ground or bridge deck level. Areas of bridges to be inspected, in particular long-span and high/tall bridges, are either inaccessible, time-consuming, or in some cases unsafe considering the height of the bridge and the rivers or canyons over which they are built.

UAV applications in the infrastructure monitoring sector have gained significant attention due to the advancement of aerial platforms coupled with the development of sophisticated sensors and image analysis software. Many transportation agencies are exploring the potential of UAVs and using them for collecting infrastructure monitoring data. UAVs can identify features including distresses, bridges, slopes, public facilities, and other infrastructure assets. Failure or delay in identifying such distress could result in injuries, risks, or even loss of life.

Although it is becoming increasingly more common, Alaska DOT&PF does not use UAVs to aid in bridge inspections. Alaska DOT&PF Part 107 FOM does outline policy and procedures for all UAS Operations but not for the actual inspection. The research team will attempt to alleviate these concerns and develop a research program to address the safe and effective use of UAV platforms for performing bridge inspections.

Research Objectives

The research objectives include (1) conducting a literature review; (2) inspection of bridges in Year I; (3) development of a workflow for 360° bridge inspections; (4) refinement of workflow based on the project committee comments; (5) inspection of bridges in Year II; (6) compilation of the study findings into a final report; (7) organizing a workshop to train Alaska DOT&PF bridge personnel.

Project Scope

The researchers collaborated with the Alaska Department of Transportation and Public Facilities (Alaska DOT&PF) and conducted the inspection of multiple bridges to identify best practices for performing aerial surveys/inspections of various bridge infrastructure elements using uncrewed aerial vehicles (UAVs). During the first two years, UAV-based data collection was performed at eleven bridges discussed below in Tables 1 and 2, respectively. In addition, two buildings and a tower were also inspected during the first and second years of field inspection studies, respectively. The workflow for 360° bridge inspections was developed while performing the Year I bridge inspections. The developed workflow was refined based on the project technical team's input and demonstrated during the Year II bridge inspections. The Alaska DOT&PF bridge division personnel demonstrated the workflow hands-on during a technology transfer workshop conducted in Year III. The research methodology and approach are outlined in the next chapter.

Table 1. Details of the inspected bridges during Year I

SNO	ID	Name	Superstructure	Length (ft)	Width (ft)	Spans	Year Built	Coordinates	Drone Airspace
1	1964	Canyon Creek	PS Concrete Girder	891	43	7	1997	60° 46' 48.9972" N 149° 25' 40.998"W	Class G
2	6020	Canyon Creek Pedestrian	Steel Girder	290	30	5	1950	60°46'44.0004"N 149°25'44.0184"W	
3	634	Twenty Mile River	Steel Girder	568	34	7	1967	60° 50' 42.0 " N 148° 59' 17.5 " W	
4	1341	Eagle River (SB Frontage)	PS Concrete Girder	416	37	3	1974	61°18'37.2564"N 149°34'49.9296"W	
5	1739	Eagle River (Briggs)	Continuous Steel Girder	611	93	3	1992	61°17'53.8656"N 149°32'23.8956"W	
6	1669	Montana Creek	Steel Truss	205	28	1	1988	62°10'41.6856"N 149°57'19.4364"W	

Table 2. Details of the inspected bridges during Year II

SNO	ID	Name	Superstructure	Length (ft)	Width (ft)	Spans	Year Built	Coordinates	Drone Airspace
7	262	Little Coal Creek	Steel Arch	268	34	1	1969	62°53'21.9"N 149°45'51.5"W	Class G
8	1121	Knik River Northbound	Continuous Steel Girder	1532	40.2	8	1965	61°28'53.4"N 149°15'09.4"W	
9	1155	Peters Creek Northbound	Continuous Steel Girder	168	42.6	3	1969	61°24'17.0"N 149°27'33.1"W	
10	1124	Matanuska River Northbound	Continuous Steel Girder	1127	40.2	6	1965	61°30'14.0"N 149°14'57.8"W	
11	539	Knik River	Continuous Steel Box Girder	506	29	3	1975	61°30'14.1"N 149°01'59.2"W	Class E floor at 750 ft

CHAPTER 2 – RESEARCH METHODOLOGY: 360° BRIDGE INSPECTION WORKFLOW

2.1 Literature Review

Several departments of transportation agencies have started using UAVs for conducting bridge inspections. Some of those studies are provided below:

Michigan Department of Transportation (MDOT) conducted a study to evaluate the application of UAVs for pavements and bridges using different sensors (Brooks et al. 2015). Minnesota Department of Transportation (MnDOT) conducted an initial demonstration project to investigate the use of UAVs for bridge inspection. A second phase of the study was conducted based on the findings from the first phase (Wells and Lovelace, 2017). Both projects inspected four bridges each at various locations in Minnesota and provided inspection assessments. In the second phase, they verified the feasibility of using a combination of optical and infrared images and videos for bridge inspection. The images were also used to generate 3D models of the area. The Oregon Department of Transportation (ODOT) identified major bridge reporting categories and provided a scale to rate the usefulness of UAVs for bridge inspections (Gillins et al. 2018).

Texas Department of Transportation (TxDOT) conducted a research project on evaluating the application of UAVs for monitoring pavement, bridge, railway corridor, and construction material inspections (Congress 2018). They were able to demonstrate a 360° inspection of a bridge section. An implementation project was also conducted to validate the TxDOT unmanned aerial vehicle systems (UAV) flight operations manual (FOM) developed in the preceding research project. Communication towers, high mast tower, intersections, building, and bridge were initially considered for UAV-based inspections (Puppala and Congress 2021). North Carolina Department of Transportation (NCDOT) conducted a study to quantify the performance of UAVs for bridge inspection. They conducted environment flow field analysis near bridge elements and concluded that bridge geometry influences turbulence and flow variation (Karimoddini et al. 2022). These often impact the operation of the UAV near the bridge elements and influence the data capture needed for conducting 360° bridge inspections.

Florida Department of Transportation (FDOT) studied the use of small unmanned aerial systems (sUAV) for bridge inspections. Specific to the bridge under-span inspections, they used a combination of payloads including two cameras, a laser range finder, a compass, a barometer, and an inertial measurement unit (IMU). These sensors allowed the drone to keep a constant elevation relative to the underside of the bridge without the drone pilot's intervention. Eight bridges in the state of Florida were inspected. For each bridge inspection, a certified bridge inspector (CBI) from the Florida Department of Transportation (FDOT) was present to evaluate the effectiveness of the aerial inspection using UAV. They stitched images and created a point cloud of the bridge structure from which the dimensions of spalling were measured. It was not clear how the models were accurately scaled to make quantitative assessments. They also suggested building models of the specific distress rather than the whole bridge to efficiently manage the data (Tomiczek et al. 2019).

Due to the battery limitations and the greater depth of inspection required for steel girder spans, the steel spans could not be inspected completely in their bridge inspections. Also, they reported some difficulty in capturing the top surface of the bottom flange of steel girders due to tight spaces within the bays. They also reported that the steel girders influenced the magnetometer on the UAV. Bridges with low clearance and tight girder spacing resulted in low light conditions, whereas bridges with high clearances generated more wind gusts (Tomiczek et al. 2019). A recent study funded by FHWA also mentioned the use of orthorectified images for quantitative inspections of the bridge elements. They magnified, cropped, and scaled an aerial image and overlaid it on the bridge plans to make measurements without the help of ground control points (Neubauer, Bullard, and Blunt 2021).

The 3D mapping of a bridge deck is similar to that of horizontal planar surfaces such as pavements, which was conducted by various studies (Congress, Puppala, and Lundberg 2018; W. Ryan et al. 2002). However, not many studies have reported the three-dimensional reconstruction of the under-span of a bridge and its limitations. A few recent studies focused on developing a workflow for conducting 360° bridge inspections. Congress et al. (2020) collaborated with transportation agencies to conduct infrastructure asset condition monitoring and assessments using UAV-CRP technology. Some of the assets including pavements, bridges, rail corridors, and construction material sites were inspected using an optical range camera mounted on UAVs. They addressed a typical challenge posed by the temporary obstructions in the 3D models by leveraging the basic principles of photogrammetry. They demonstrated qualitative inspection and a quantitative inspection of bridges. The former inspection was accomplished using image frames and the latter was performed using a 360° bridge model processed further into four orthomosaics representing the bridge faces (Congress et al. 2020).

Current Challenges to 360° Bridge Inspections

Bridges, unlike other structures, offer several unique challenges for conducting inspections. While some of the bridge areas are easily accessible, depending on the bridge characteristics and surrounding terrain, some areas are inaccessible and provide poor conditions for data capture using UAVs. A significant knowledge gap about conducting 360° bridge inspections is identified in the review of the current literature. Though several agencies and practitioners own a wide range of UAV fleets, there seems to be a lack of knowledge on a methodology to conduct 360° bridge inspections. Partly, it can be attributed to the need for several iterations and fine-tuning of the workflows to coordinate data collection and processing to achieve the objectives of a 360° bridge inspection. The natural terrain features around the bridge such as vegetation, water bodies, and other factors pose challenges to conducting several iterations for obtaining high-quality images. Multiple iterations of processing these several data-intensive images, not to mention the higher lengths and widths of the bridges, will only exacerbate these challenges. Further, on the data processing and analysis side, a few bridge engineers are using individual qualitative images to orthorectify the view of the structure and overlay on the bridge plans. Although this is an encouraging practice, the chances of having the camera, mounted on the UAV in flight, aligned perpendicular to the bridge element under focus is difficult due to the wind conditions and the unreliability of the relatively poor/distorted views provided by the first-person view (FPV) cameras additionally mounted on the UAV. The current study aims to address these challenges by providing a methodology and several key observations for a wide range of bridges as discussed in the below sections.

2.2 UAV Equipment

Different types of UAVs attached with various sensors were used to conduct the bridge inspections (Table 3).

Table 3. Details of uncrewed aerial vehicles used for inspections in this study

Drone Make/ Model	Approximate cost with accessories (USD)	Takeoff Weight (kgs)	Flight Time per Battery Set (Min)	Camera Sensor (s)	GNSS Geotagging	Vision System and Obstacle Sensors	Operating Temperature Range	Operating Frequencies (GHz)
DJI Matrice 310 RTK	30,000	9	45-50	H20T Wide Camera: 12 MP 1/2.3" CMOS (24mm Focal Length, 82.9° DFOV) Zoom Camera: 20 MP 1/1.7" CMOS (23x Hybrid Optical Zoom, 200x max zoom) Radiometric Thermal Camera: 640x512, 30Hz (40.6° DFOV)	Yes	Dual-vision and Time of Flight sensors on all six sides	-4° to 122° F (-20° to 50° C)	2.48 and 5.85
DJI Matrice 210 RTK	15,000	6.4	24-26	Zenmuse X4S camera (global shutter) & Zenmuse XT2 (Optical and Infrared sensors)	Yes	Stereo vision sensors on the front and bottom, infrared modules on top, and two ultrasonic sensors at the bottom	-4° to 113° F (-20° to 45° C)	2.48 and 5.85
Skydio 2	2,499	0.8	18-20	In-built optical camera 1/2.3” CMOS 12.3MP	No	NVIDIA Tegra TX2 using 45 megapixels of visual data from six 200 degree color cameras	23° to 104° F (-5° to 40° C)	2.48, 5.24, and 5.85
DJI Phantom 4 Pro V2	1600-2000	1.4	24-26	In-built optical camera (global shutter). 1” CMOS Effective pixels: 20 MP	No	Forward, Backward, and Downward Vision Systems. Front & Rear Obstacle Avoidance. Left & Right Infrared Obstacle Avoidance	32° to 104°F (0° to 40°C)	2.48 and 5.85

Crew

- The crew consisted of multiple Federal Aviation Administration (FAA)-certified drone remote pilots in command (RPICs) and visual observers (VOs). Based on the complexity of the inspections, VOs were placed at different locations and communicated using walkie-talkies/hands-free headsets connected to local frequencies.

2.3 Data Collection

2.3.1 Planning and Reconnaissance

- Planning of the bridge inspection started with studying the bridge plans and breaking down the inspection task objectives with the bridge inspector. Online records and Alaska DOT&PF's bridge inventory files were accessed to understand the existing conditions and the presence of potential obstructions to the UAV flight. In addition, traffic directions and allowable speed were accounted for to identify preliminary take-off and landing spots, RPIC positions, and VO positions.

- The number of flights and inspection time were roughly assessed based on the sensor specifications, required detail, and surface area of the bridge elements. It is recommended to use an on-site charging station to be efficient and get the most benefits from aerial inspection of bridges, especially large bridges and ones located in remote areas.

- Flight planning, safety briefings, field reconnaissance, equipment setup, mission flights, and debriefings at the site are important steps in field asset inspections. Except at locations with dense vegetation, bridge deck mapping was conducted using a pre-planned flight plan, which was prepared and loaded onto the remote controller (RC) before reaching the site. Also, if flight inspections need to be performed in restricted airspace, it is recommended to obtain FAA authorization first and unlock the drones before reaching the site. This helps in dealing with the unavailability of the internet or cellular connections at the site to load the map.

- During the day of data collection, a safety briefing and the objectives of the inspection were communicated to the data collection team. The positions of the VOs and the connectivity of the walkie-talkies/hands-free headsets were verified. The data collection team members were also instructed about the measures to be followed in areas with potential wildlife interactions.

- Site reconnaissance was conducted to identify any potential obstructions to the planned manual and automated flights. It was crucial to account for unfavorable conditions that may not have been identified during the online reconnaissance and amend the flight plans accordingly. The equipment was set up and tested before flying over the actual assets. Data collection was conducted as per FAA Part 107 guidelines.

2.3.2 360° Inspection

- The 360° inspection of each bridge was conducted by dividing the field operations into three stages. First, the bridge deck was mapped using nadir images with a minimum of 80 percent overlap (Figure 1a). Second, the oblique images of the bridge were captured on both sides (Figure 1b). Third, the images of the under-bridge spans (Figure 1c), pier caps (Figure 1d), pier verticals (Figure 1e), and abutments (Figure 1f) were captured. Each of these Figures 1a - 1f depicts the location of the images with respect to the inspected bridge elements.

2.3.2.1 First Two Stages

- During the first two stages, an RPIC and a VO were stationed near each abutment of the bridge. While planning the flight missions, efforts were made to minimize the UAV flight time directly above the traffic lanes. Whenever there was an instance of directly flying over the traffic lanes, two VOs were placed at a safe offset distance, depending on the speed of the road, on both ends of the road to communicate when vehicles were approaching.

- For each side of the bridge, the drone was flown using multiple remote controllers (RCs) capable of being operated by multiple RPICs. The gimbal and camera on the UAV were set up under the free mode, which essentially detaches the orientation of the gimbal from the direction of the flight and focuses on the direction based on the RC inputs provided by the RPIC.

- When the drone approached each abutment, the UAV was operated by the nearest RPIC, and the gimbal was controlled by the farthest RPIC. This ensured safety and efficiency when collecting bridge imagery in challenging terrains with vegetation and inaccessible areas. This also allowed the data collection team to fly the drone parallel to the longitudinal direction of the bridge and rotate the camera to face the bridge at the desired fields of view and angles.

- The oblique images were captured along horizontal legs distributed along the plane perpendicular to the bridge deck (Figure 1b). The oblique images collected along the lower-level horizontal flight legs to capture the under-bridge elements were focused on the nearest pier, until the middle of the span, and then focused on the next pier.

- Not all drones can support dual RC control. Therefore, depending on the complexity of the inspections and availability of equipment, a few inspections were also conducted using drones capable of only being operated by a single RC controlled by an RPIC.

2.3.2.2 Third Stage

- During the third stage, due to the unavailability of a stable GPS connection and the presence of dense vegetation, the under-bridge inspection was conducted through manual flights with the camera triggered by an intervalometer. The RPIC and the VO were positioned under the bridge for a better line of sight (LOS) and connectivity between the RC and the UAV.

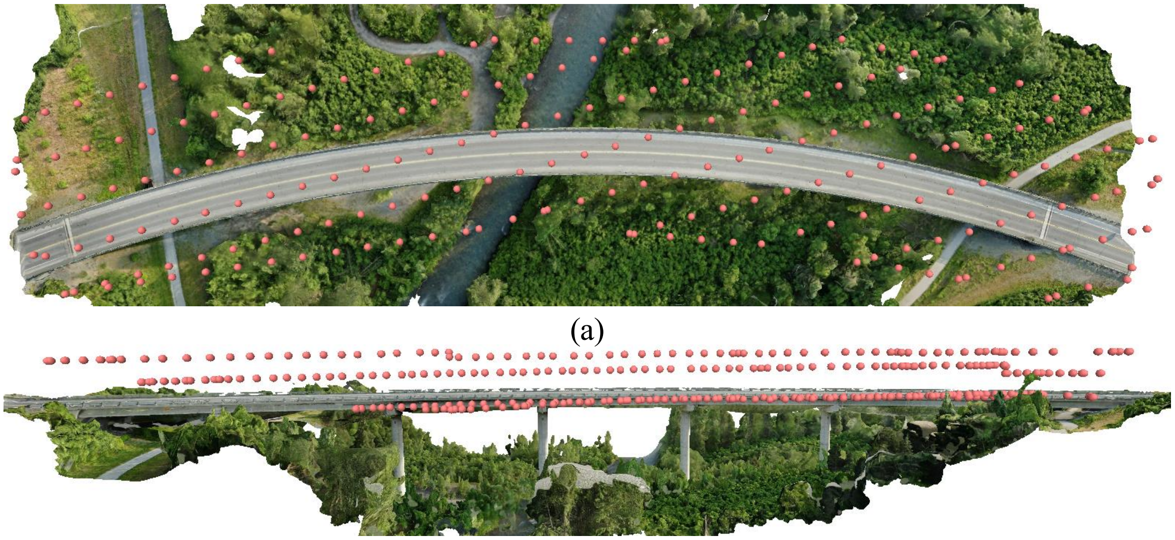
- The images of the under-bridge spans were captured through horizontal flight legs, distributed across the width of the bridge, and flown along the longitudinal direction of the bridge (Figure 1c). The brightness of the images was enhanced unrealistically to counter the shadows and observe the conditions existing underneath the bridge deck. However, proper care must be taken not to operate the same camera settings, programmed for low light conditions, in areas with ambient light conditions because they make it difficult for the RPIC to spot the presence of obstructions through the camera view.

- While executing the horizontal legs capturing the under spans, it is important to capture the pier caps and abutments to provide context to the pictures, which is necessary to process the imagery using photogrammetric techniques. Each pier cap was also captured by flying the drone in a horizontal orbit around it (Figure 1d). Each pier length was captured in four vertical flight legs distributed in equal angles around the pier (Figure 1e). Six vertical legs can be used for large column diameters.

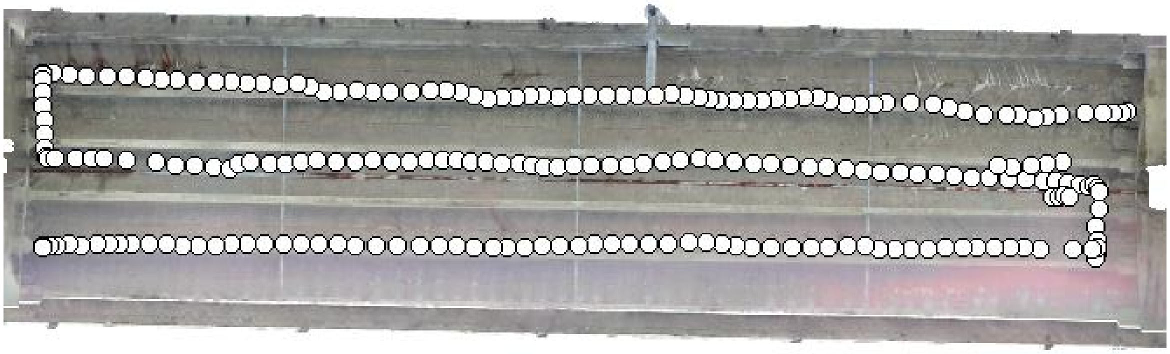
- During the inspections on pier verticals in the third stage, provided that there was access to the base of the pier, the RPIC was either standing in-line or perpendicular to the line joining the positions of the drone and the pier. The in-line position is accomplished by having the UAV in between the pier and the RPIC. Perpendicular is when the RPIC positions in such a way as to view the distance between the UAV and the pier.

- Depending on the complexity of the area, that is, the presence of vegetation or other obstructions, the RPIC can adopt in-line or perpendicular positioning. In addition, a VO can be simultaneously used at perpendicular and in-line positions, respectively, for the above cases.

- Abutments were captured through horizontal flight legs flown parallel to the width of the bridge and distributed along the depth of the bridge (Figure 1f). Depending on the clearance depth available near the abutment slopes, the horizontal legs can be distributed horizontally at different lateral distances from the abutment. A debrief of the field inspections was conducted at the end of each inspection.

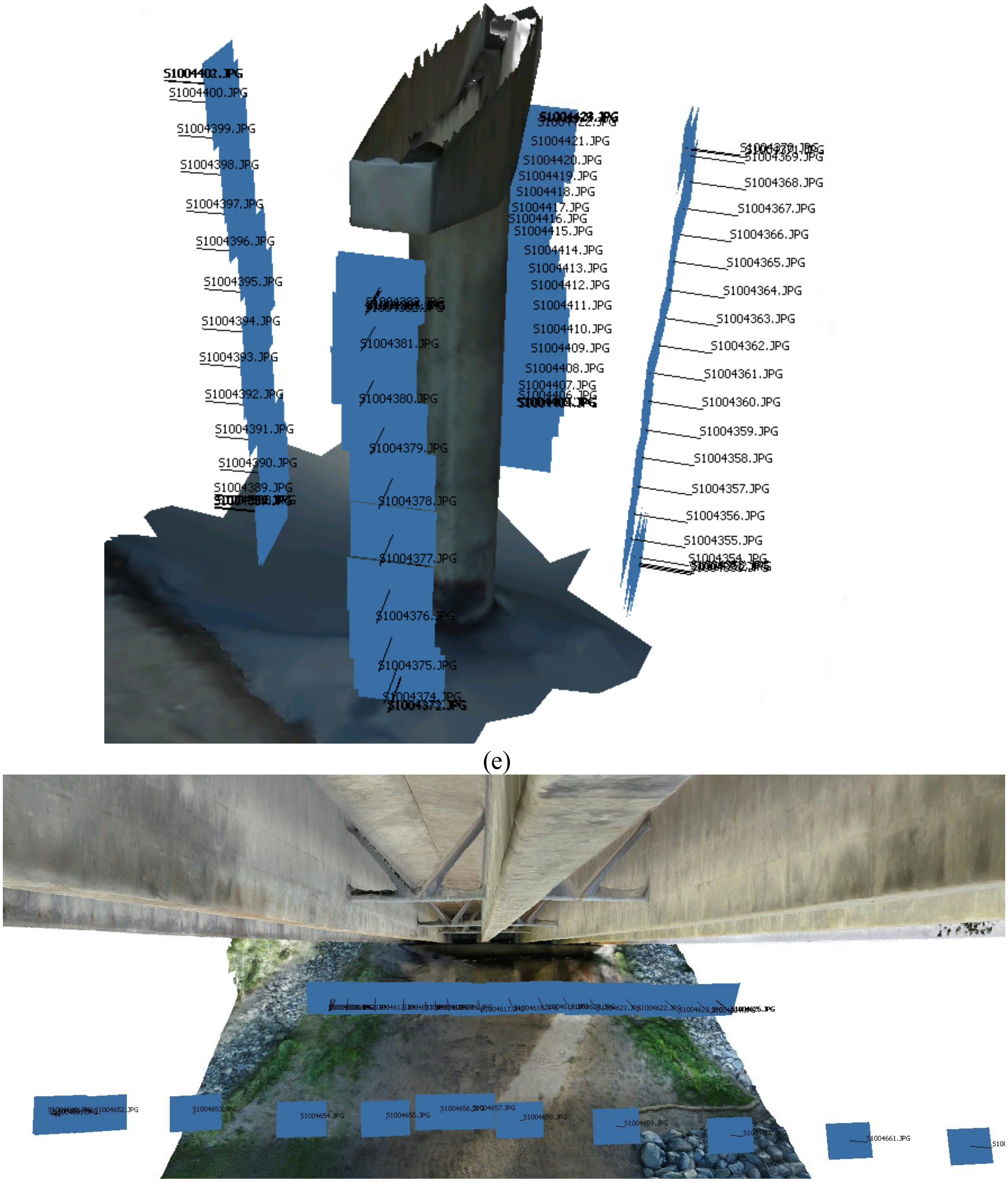

(a)

(b)



(c)

(d)



(e)

(f)

Figure 1. Typical UAV flight paths for 360° Bridge Inspection (a) First stage: Nadir flights (b) Second stage: Oblique flights (c) Third stage: Under spans (d) Third stage: Pier cap (e) Third stage: Pier verticals (f) Third stage: Abutment

2.4 Data Sorting and Storage

Generally, the use of an SD card with storage space large enough for the whole day's inspections is recommended. The aerial images from the drone were copied onto the laptop/external solid-state drive (SSD) in the field whenever there was a long break or after the completion of either the top deck or under-bridge inspections.

- Firstly, the aerial data of each bridge were segregated according to the date and time stored in the metadata of the images. Secondly, the aerial data of each bridge collected with multiple sensors were also segregated. Subsequently, the red-blue-green (RGB) images of the bridge were classified into top deck and under-bridge folders.

- In the top deck folder, the data were sorted into nadir and oblique images captured during the first and second stages of data collection, respectively. Subsequently, oblique images were sorted based on the direction in which they were facing the bridge.

- In the under-bridge folder, the images were classified according to the bridge element being inspected. The image folders of each span, pier, pier cap, and abutment were numbered based on the bridge inventory files and placed in sub-folders created in the under-bridge folder. A backup of all these folders was created on an external hard disk.

- At the end of each day's data collection, the SD card could be formatted after creating a backup of the images stored on the laptop/SSD.

- After processing the data models from the aerial images, the 3D model was also used as a reference to retrieve the stored aerial images. This was found to be very helpful while inspecting elements, especially under-bridge spans, where unreliable location information and similarity of elements (which are generally inspected closely with less context captured in the frames) made it hard to even conduct qualitative inspections.

2.5 Data Processing and Analysis

- The aerial images of the bridges were processed to generate a dense point cloud model, mesh, render texture, digital surface model (DSM), tiled model, and orthomosaic. The dense point cloud model is a database formed by points that are accurately defined with location coordinates and color information. A mesh is formed by connecting each set of three adjacent points into a triangular face to form the surface of the model rendered with textures derived from the images. A DSM is a raster image with color-coded pixels, arranged in rows and columns of an image, with color representing the elevation of the corresponding point in the image.

- An orthomosaic is a map generated by correcting the images for distortion and providing a stitched image with a uniform scale to measure the horizontal distances between features on the two-dimensional image. Also, an orthophoto, which is an orthorectified version of each image, can be output by correcting the geometry of objects captured in those images. A system with a Windows 64-bit operating system with Intel® Xeon® Gold 6148 CPU with 2.40°GHz, 192 GB RAM, and two NVIDIA V100 GPUs were used to process all the aerial imagery and output these 3D mapping products as described as follows.

    - Typical data processing and model generation workflow includes the following steps. Ground control points or manual tie points can be identified and marked in the corresponding images. All images were aligned and stitched using guided image matching to generate tie points and key points that were subsequently used to produce a high-quality dense point cloud model.

- The dense point cloud model or the high-quality depth maps were used to generate a mesh model, and the texture was derived from the images. A tiled model was generated using the already generated depth maps. A DSM was developed from dense point cloud or depth maps. Using ultra-high-quality depth maps yielded higher-resolution DSMs. It should be noted that generating a DSM was most beneficial in the case of deck mapping only. A relative DSM in any other viewpoints will provide the relative difference in distances between the viewpoint and the areas within the field of view.

- An orthomosaic can be generated by projecting the images on either a DSM or a mesh surface. Orthomosaics of the bridge deck and under-bridge spans are useful to not only identify the distress/conditions but also to make quantitative assessments. However, orthomosaics can be generated by following slightly different workflows.
  - The orthomosaic of the bridge deck was typically obtained by disabling the under-bridge images and processing the deck images using a pre-defined coordinate system.
  - The orthomosaic of the under-bridge spans was generated by following these steps: (1) disabling the deck images, (2) enabling the back-face culling option, (3) changing the view to look at the under-bridge spans, and (4) restricting the focus region to an elevation higher than the base of the column.
- Further, the scaled images can be used to make measurements by importing them into software that can process a Geo-Tiff file.

CHAPTER 3 – BRIDGE INSPECTION DETAILS

360° inspection of one of the bridges inspected in the study is discussed below for reference. The other bridge inspection data was provided to the bridge division personnel.

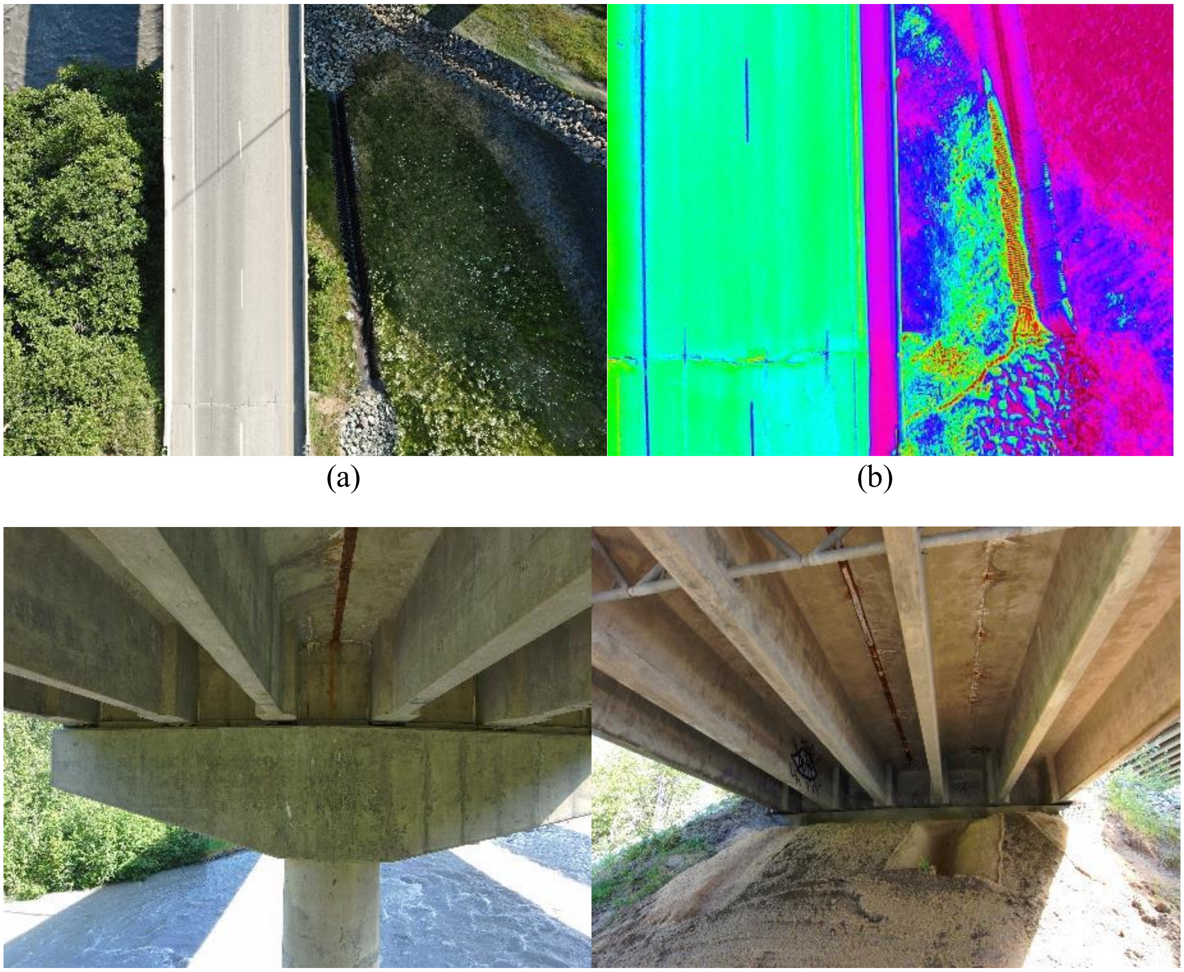
3.1 Eagle River Southbound Bridge (1341)

3.1.1 Bridge Details

This is a three-span prestressed decked-bulb-tee bridge on hammerhead piers with concrete columns. It has reinforced concrete deck material and asphalt wear surface. It has a 416 ft long and 37 ft wide bridge deck supported by two piers along three spans in between the abutments. The bridge deck serves as a two-lane one-way road with the traffic approaching from the northeast and heading towards the southwest. The northeast end of the bridge connects the road to Palmer (FE) and the southwest end connects the road to Anchorage (NE). The areas surrounding the bridge abutments are densely vegetated. The base areas of the two piers are surrounded by a fast-flowing stream from southeast to northwest. According to the United States Geological Survey (USGS), the areas surrounding this bridge experienced an earthquake of magnitude 7.1 in 2018 (Congress et al. 2023).

3.1.2 Aerial Inspection Highlights

Multiple RPICs and VOs, located on the opposite abutments, were used simultaneously to collect the aerial imagery of the bridge. The nearest RPIC controlled the navigation of the UAV while the farthest RPIC controlled the movement of the gimbal. The responsibilities between the RPICs were swapped when the UAV approached the farthest RPIC. It took approximately five hours (~5 hrs) to collect a total of 1624 images that were used in processing the 3D models. The time also includes the ground movement of the crew, capturing of videos, and some delays in UAV flights caused due to the movement of the ground vehicular traffic, which was provided the right of way throughout the UAV-based inspections. The lessons learned in collecting and processing the bridge sites were helpful in successfully generating a single 360° model of this bridge. Besides, a camera with both optical and infrared sensors was used to evaluate the feasibility of identifying cracks and the effect of thermal loading on distress identification. Some of the images captured during the aerial inspection of super- and sub-structure bridge elements are provided in Figure 2.

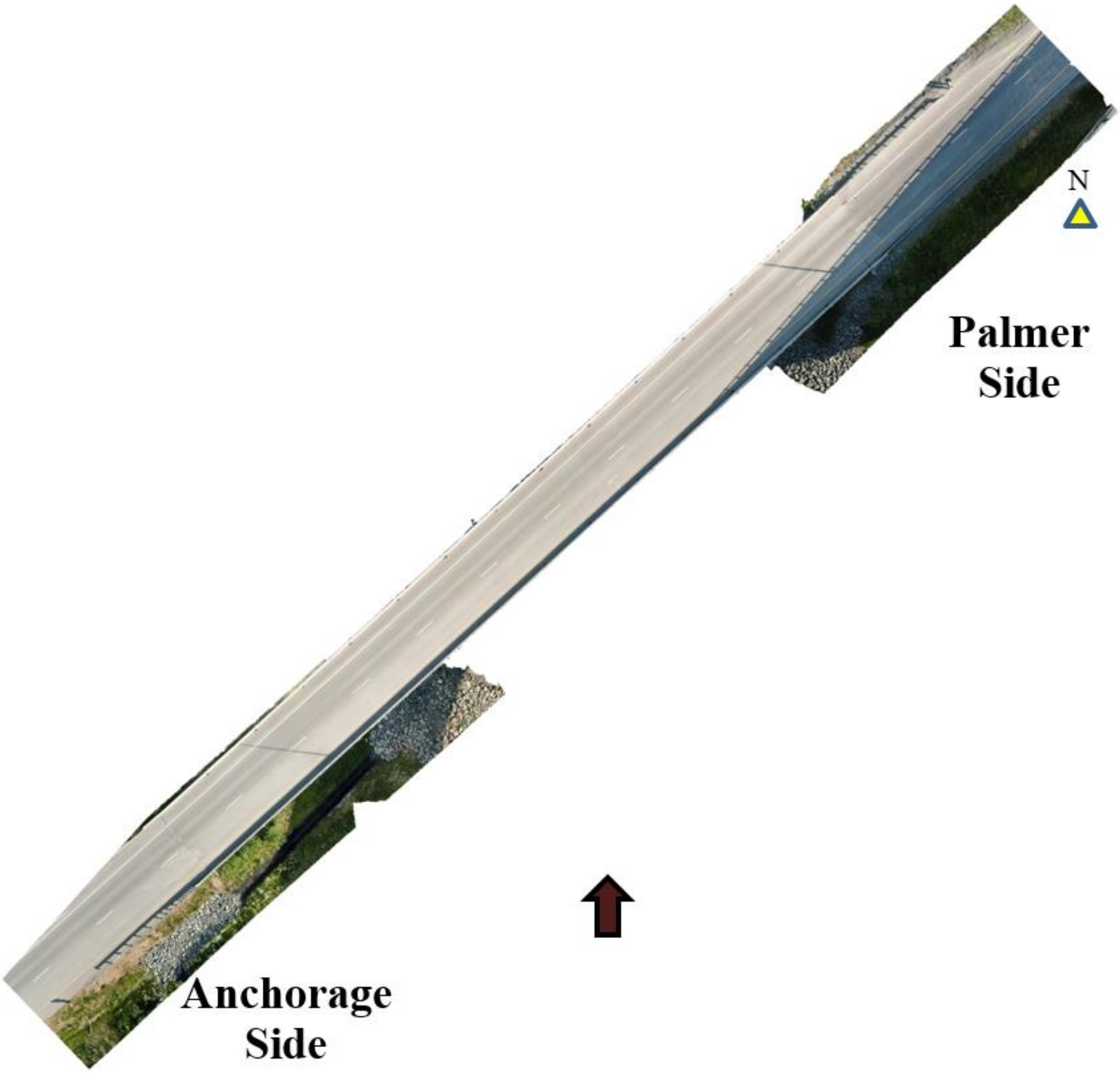


(a) (b)

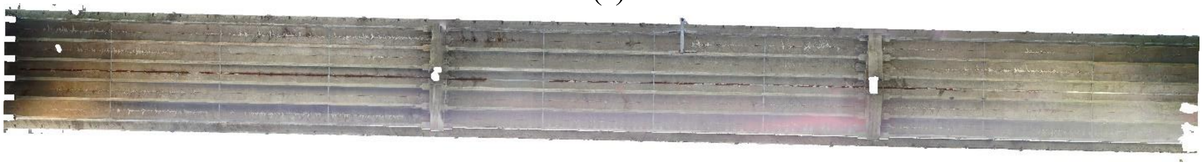
(c) (d)

Figure 2. Aerial inspection of the Eagle River Southbound bridge elements (a) RGB image of bridge deck (b) Infrared image of bridge deck (c) Aerial inspection of pier cap (d) Aerial inspection of abutment on Palmer side.

It took approximately sixteen hours (~16 hrs) to process the aerial imagery and generate models having a total data size of 925 MB. The orthomosaics of the bridge deck, under-span, and both side faces having a total data size of 63 MB were generated as shown in Figure 3. It can be observed that there is a 93 % reduction in data storage requirements while storing and using orthomosaics instead of 3D models. The viewpoint of the 3D model, shown in Figure 4a, is indicated by the maroon arrow shown in Figure 3a. The left and right sides of the under-bridge span orthomosaic, shown in Figure 3b, indicate the Anchorage (NE) and Palmer (FE) sides of the bridge, respectively. The orthomosaics of the north and south sides of the bridge are shown in Figures 3c and 3d, respectively. The conditions of the girders, pier caps, bearings, and other bridge fascia elements were inspected.



(a)



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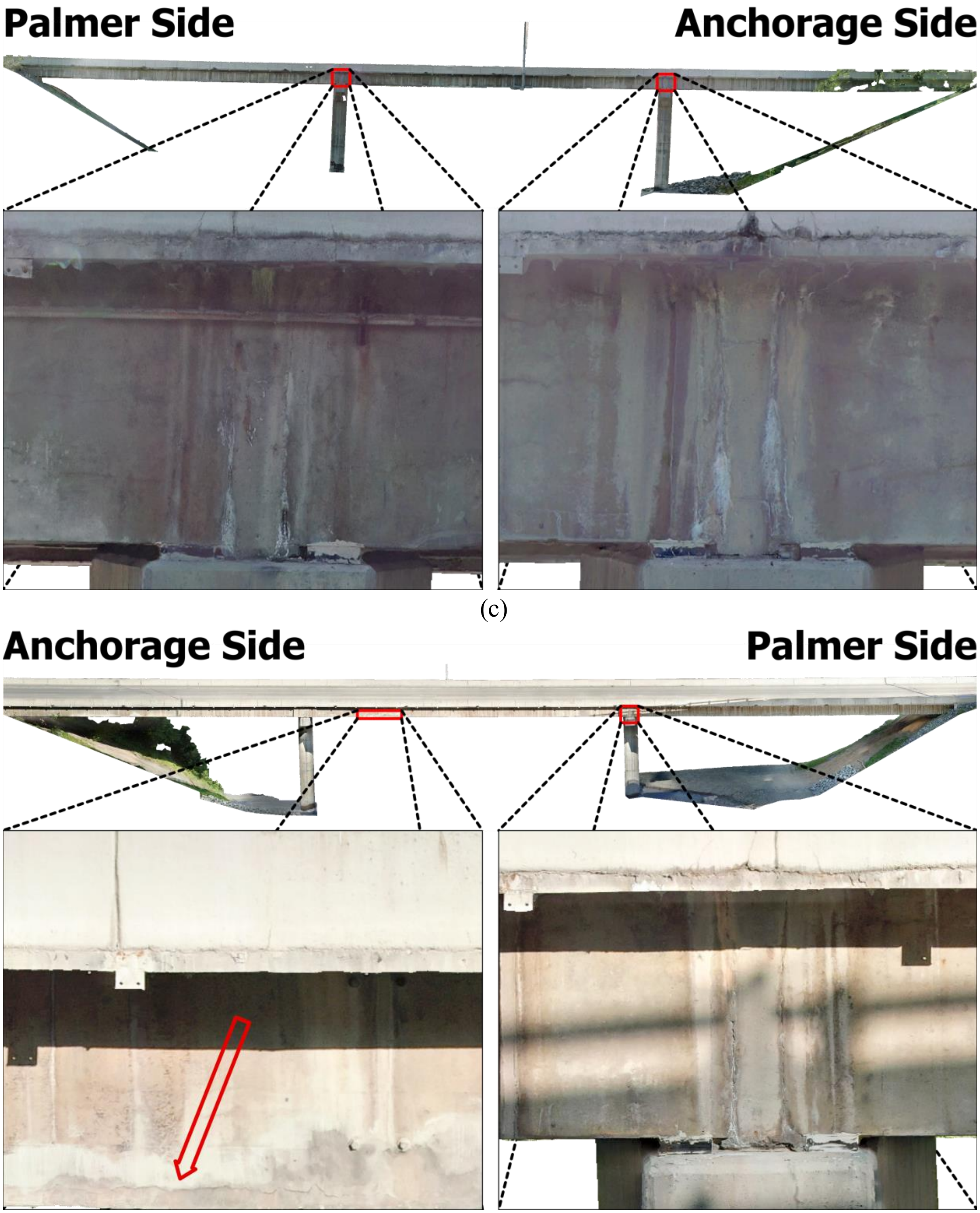


(c)

(d)

Figure 3. 360° Inspection of Eagle River Southbound Bridge (a) Deck (b) Under-span (c) North face (d) South face

3.1.3 Condition Assessments

Patched areas, cracks, and efflorescence were identified on both faces, especially on the south face. Some of the cracks caused by formwork can also be identified in the infrared images shown in Figure 4. The routine bridge inspection report prepared for this bridge by Alaska DOT&PF in 2019 was accessed to make a comparison with the aerial imagery and 3D models. Some of the assessments identified in both inspections are asphalt cracking, spalling, efflorescence, rust stains, and erosion.

Efflorescence and rusting of the flange seam can be observed in Figure 3b. Rail end spalling and exposed reinforcement identified during the traditional routine inspections in 2019 can be observed in Figure 4b. The same distress can be observed in both the aerial RGB image and the 3D model shown in Figures 4c and 4d, respectively. The asphalt crack formed due to the 2018 earthquake can also be observed in Figure 4d. Cracks, formed due to patchwork, can be observed in both infrared and optical images shown in Figures 4e and 4f, respectively.

The importance of the thermal loading and its angle of incidence for the identification of cracks, formed due to formwork, can be observed from the inability to distinguish cracks in infrared images, even though they are visible in optical images shown in Figures 4g-j. Concrete falloff near the patched area on the south face girder can be observed in Figure 4k. It can be observed that the optical illusion created by the shadows behind the distress and the vegetation in front of it almost obscures the presence of the distress. However, multiple images collected following the photogrammetric principles helped in identifying the distress and confirming its presence by leveraging multiple views of the bridge in the 3D model.

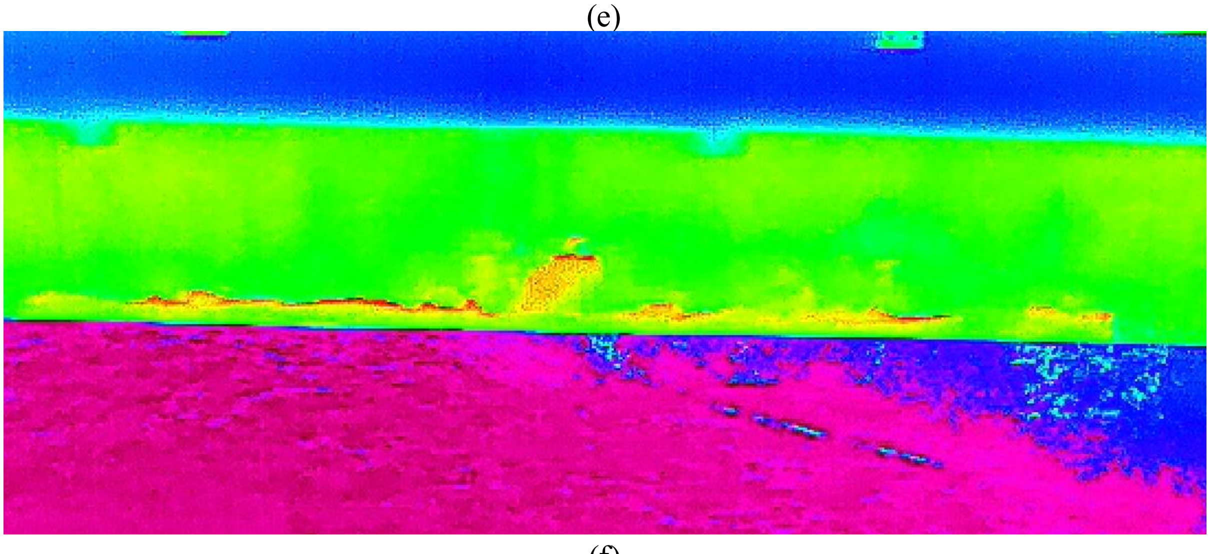
(a)

(b)

(c)

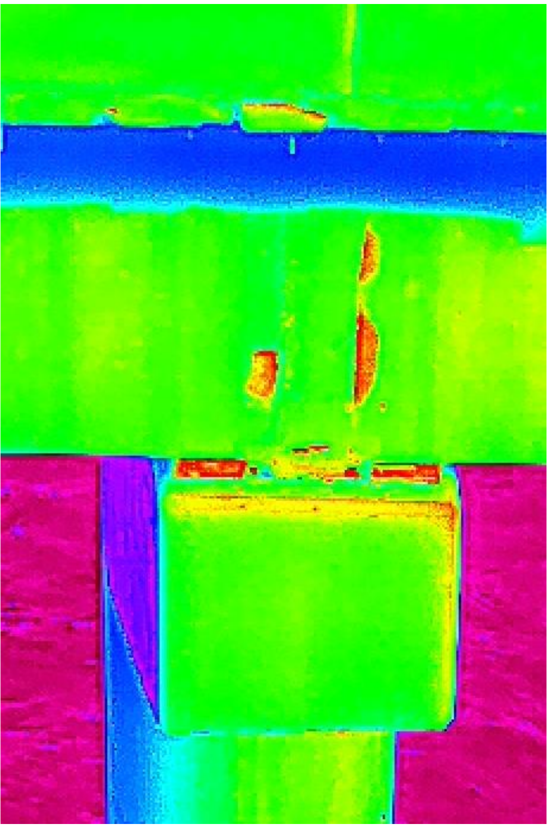
(d)

(e)



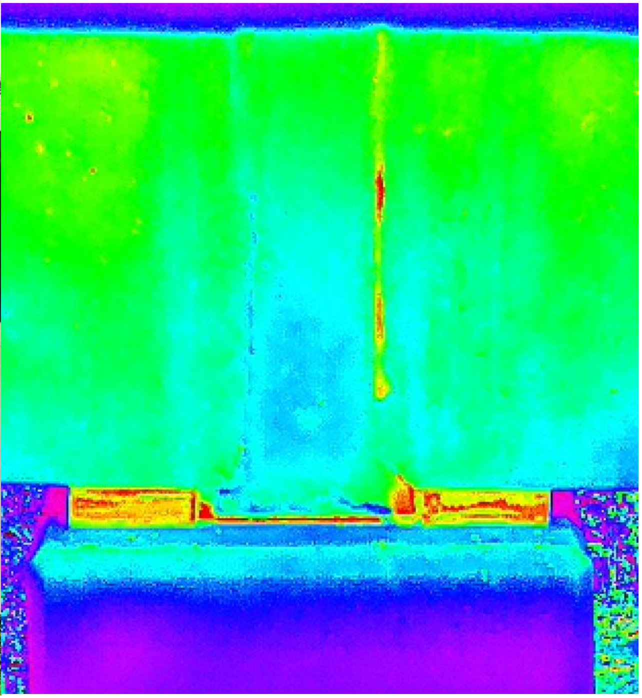
(f)

(g)



(h)

(i)



(j)

(k)

Figure 4. Eagle River Bridge condition assessments (a) 3D model viewed from the south direction (b) Railing end spall identified during the routine inspections in 2019 (c) Rail end spall in the aerial RGB image (d) Railing end spall and asphalt crack in the 3D model viewed from the southeast (e) Optical image of patchwork crack (f) Infrared image of patchwork crack (g) Angle of incidence: optical image of formwork cracks (h) Angle of incidence: infrared image of formwork cracks (i) Thermal loading: optical image of formwork cracks (j) Thermal loading: infrared image of formwork cracks (k) Concrete fall off on south side face of the bridge.

3.1.4 Key Observations

- Flying from the slope uphill and landing the drone at the slope downhill with communication between the RPICs and/or VO was found to be effective and safe for transporting the drone equipment to conduct under-bridge inspections.

- UAV flights for inspecting areas near streams might experience sudden gusts so maintaining sufficient clearance/offset distance from the bridge elements is recommended.

- Thermal loading and its angle of incidence influence the ability to identify cracks/distress on the infrared images of a bridge.

- Shadows and obscured locations are observed to create doubt about the presence of the distress; however, multiple images captured to provide the 360° view of the bridge help in solving some of these challenges.

CHAPTER 4 - APPLICATIONS OF UAVS FOR HIGHWAY BRIDGE INSPECTIONS

UAV images, based on how they are captured, enable two types of bridge inspections (1) qualitative inspection (2) quantitative inspection. The latter inspection type needs sufficient overlap to stitch and align images, unlike the former type. The need for building a 360° model will be considerably reduced if the objective of conducting the UAV flight is to perform a qualitative inspection of a critical member or some other special inspection (truck/boat strike or natural disasters). A few advantages of these qualitative inspections using UAVs are (1) helping the bridge inspector to safely and quickly get visuals of bridge elements located in hard-to-reach areas without the need for costly and time-consuming equipment (2) they may not take a long time for data collection.

For quantitative inspection, data collection needs to be planned with the desired overlap to build a 'data-intensive' 3D model and process it to generate 'less data-intensive' orthomosaics that offer high-definition scaled views of the bridge conditions. Storing a 3D model will provide context to the individual aerial images, especially of bridge under-span elements. However, if the agencies are concerned with the data sizes of the 3D models, they can be discarded after generating all orthomosaics.

Considering the limitations in time and data storage capacities needed for a quantitative inspection, below are some cases that might benefit from such inspections: (1) generating 3D models and orthomosaics of all faces immediately after the bridge construction can be useful for DOT agencies to perform quality control and also understand the causes of any future issues by having a 3D digital baseline dataset to trace back any distress causing phenomena (2) 3D models and orthomosaics can be used to quantify the distress. Further, when generated with a sufficient temporal resolution, they can also help in tracking the propagation of the distress and achieve timeline monitoring (3) developing 3D models and orthomosaics can be beneficial for routine inspections of steel-truss bridges and multi-span bridge structures over stream crossings as using bucket truck or other traditional inspection methods can be time intensive and incurs higher traffic management and delay costs compared to UAV-based inspections. The frequency of UAV-based inspections of a structure can be decided based on engineering judgment as there are many factors to consider such as the critical nature of the asset, the current level of condition and rate of progression of damage, the extent of inspections needed, and others (4) creating localized 3D models and orthomosaics to evaluate the potential distress area immediately after an emergency/natural disaster/bridge strike can be useful due to less deployment time of the UAVs and unfamiliarity of the bridge conditions to withstand loads exerted by the use of traditional inspection equipment. Based on the observations made in this study, the potential applications of UAVs for highway bridge inspections are listed in Table 4.

Table 4. Potential applications of UAVs for highway bridge inspections

SNO.	Inspection Category	Application of UAVs	Remarks	Recommendation Scale
1	Inventory Inspection	Can be used for generating the scaled views of all bridge faces and mesh models for inventory purposes and digital twin applications	UAVs can be used as an economical and safe data collection tool to document as-built conditions of the bridge immediately after construction	10 (Highly favorable)
2	Routine Inspection	Can be used for generating the scaled views of all bridge faces and mesh models for digital twin applications	The application of UAVs for routine inspections can also lead to damage, in-depth, or special inspections during the same field operations and also provide base information to plan other inspections at a later date	8
3	Damage Inspection	Can be used for generating the scaled views and mesh models of the damaged element(s) under inspection	Quick deployment of compact UAVs helps in conducting the reconnaissance surveys of the bridge condition immediately after any incident requiring a damage inspection	6
4	Special Inspection	(1) Access hard-to-reach areas and quick capture of bridge element conditions; (2) Conduct localized inspection mapping	Quick deployment of compact UAVs helps in conducting the preliminary reconnaissance surveys of the bridge condition immediately after any incident requiring a special inspection. It also helps in planning subsequent in-depth	5

			inspections and/or repairs needed	
5	In-depth Inspection	For above water inspections: (1) Provide access to hard-to-reach areas and facilitate quick capture of bridge element conditions; (2) Conduct localized inspection mapping	Preliminary information for in-depth inspections can also be combined with the use of UAVs for routine inspections, which will result in reduced overall inspection time and costs	4
6	Fracture Critical Member (FCM) Inspection	(1) Access hard-to-reach areas and quick capture of bridge element conditions; (2) Conduct localized inspection mapping	UAVs can reduce the rental time of traditional inspection equipment by providing visuals and surficial geometry of outer bridge elements before performing the FCM inspections	2
7	Underwater Inspection	Can complement above-water condition information but cannot be used directly for underwater inspection	Erosion areas near the banks can be inspected to estimate the volume of erosion gullies to be filled	0 (Not favorable)

CHAPTER 5 - CONCLUSIONS

This study developed a workflow and evaluated its feasibility for conducting 360° inspections of various bridges using 3D models and orthomosaics generated from aerial images collected using UAVs. The coordination, planning, collection, processing, and analysis steps outlined in this study provide a holistic idea about conducting 360° inspections of various bridges. The digital replicas of the bridges helped conduct quantitative assessments. As reported by previous literature, orthorectified and stitched images being overlaid on the bridge plans were found to help provide scaled views of the bridge elements and identify the spalled areas, rusted areas, cracking extent, and other distress. Further, the practice of using orthomosaics of all bridge faces instead of 3D models was found to be effective in reducing the data storage requirements of the bridges considered in this study by more than 90%. The approach demonstrated in this study is expected to contribute to an increase in the applications of UAVs for conducting 360° bridge inspections across the U.S.

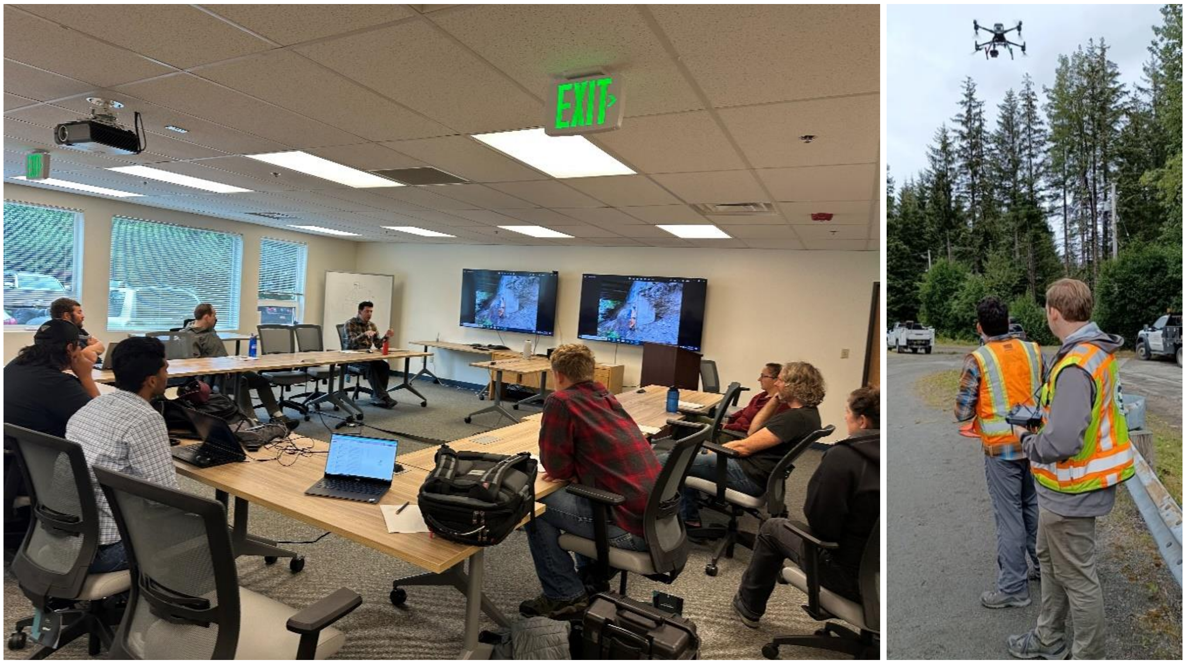
Besides, the 360° digital model was also able to remotely provide information about the bent elements of the steel truss, which reduces the need for using special crew lift equipment to spot them on a steel truss bridge and any associated traffic delay due to lane closures. Moreover, the influence of thermal loading in identifying the conditions of the bridge elements in infrared images was also demonstrated and discussed. Individual aerial images of bridges, especially under-bridge spans, might look the same, and can be difficult to differentiate the location. Poor GPS conditions also contribute to this issue. Hence, 3D models provide context to the images and serve as a repository of inspection images.

Simultaneously using multiple RPICs and multiple drones can be explored to reduce the data collection time, however, the objectives and planning of operations need to be discussed before coordinating the collection of complementary data.

CHAPTER 6 - TECHNOLOGY TRANSFER WORKSHOP

During the technology transfer workshop conducted in Year III, the bridge division personnel of Alaska DOT&PF was provided with a detailed seminar on the developed workflow for 360° bridge inspections using UAVs. Subsequently, they used UAVs to conduct a 360° inspection of a bridge over Mendenhall River. A recent glacier melt in Juneau, Alaska, has caused a significant flooding event near this bridge shown in Figure 5. Multiple drone pilots and visual observers were split into groups to simultaneously conduct data collection of bridge elements in different stages.

Figures 5a and 5b show Jesse Escamilla, Design Squad 1 Lead, Bridge Design Division, Alaska DOT & PF, leading the planning of flight missions and UAV-based field inspections, respectively, during the hands-on workshop. Some of the bridge personnel, who were FAA-certified drone pilots, were divided into groups and assigned a visual observer to carry on the inspection of specific bridge elements, as shown in Figure 5. The bank erosion that occurred due to the flooding and the highest water level due to the flooding can be observed by the moisture marks highlighted on the bridge shown in Figures 5d and 5e. Figure 5e shows the 360° bridge inspection conducted using a drone and the view from the camera inspecting the bridge elements. These inspections post-disaster events not only help in ensuring the optimal performance of the bridge condition but also help create baseline data for future reference. Overall, the workshop was successful in disseminating the details of the workflow and providing a hands-on experience to the bridge personnel for conducting 360° bridge inspections using UAVs.



(a) (b)


Highest water level indicated by moisture
Bank Erosion
Drone

(c)

(d) (e)

(f)

Figure 5. Mendenhall River Bridge Inspection post flooding due to glacier melt (a) Mission planning (b) Stage I: Deck inspection (c) Stage III: Underspan inspection (d) Stage III: Bank erosion (e) Stage III: Close range inspection of the bridge pier cap (f) Stage III: Abutment inspection

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