

Eye in the Sky: 360° Inspection of Bridge Infrastructure Using Uncrewed Aerial Vehicles (UAVs)

Transportation Research Record
2024, Vol. 2678(4) 482–504
© The Author(s) 2023
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/03611981231185138
journals.sagepub.com/home/trr
S Sage

Surya Sarat Chandra Congress¹ , Jesse Escamilla, III²,
Hiramani Chimaurya³ , and Anand J. Puppala³ 

Abstract

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 inspections and realize benefits in relation to access, cost, and safety. Federal and state DOTs have conducted several studies on the application of uncrewed aerial vehicles (UAVs) for bridge health monitoring. This study identified the existing knowledge gap in performing 360° inspection of bridges. In this current research, UAVs were demonstrated for conducting 360° inspections of three different bridges in Alaska. The locations of the aerial images during the inspections were also pictographically represented to provide a holistic idea 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. Infrared imagery was also collected to identify the effect of thermal loading in assessing the conditions of the bridge elements. 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 applications of UAVs for conducting 360° bridge inspections across the U.S.

Keywords

infrastructure, bridges, UAV, 360° inspection, steel truss

Bridges play a key role in connecting the transportation infrastructure network. As per the recent 2021 American Society of Civil Engineers (ASCE) report card, 42% of 617,000 bridges in the U.S. are over 50 years old. Moreover, 7.5% of the nation's bridges are considered structurally deficient, or in poor condition, and 178 million trips are taken across these bridges every day (1). This also highlights the need for identifying tools that can help conduct frequent monitoring and provide an idea about the condition of the bridge.

An uncrewed aerial vehicle (UAV) equipped with an optical camera sensor is the most common and low-cost assembly used in recent times for monitoring various civil infrastructure assets such as pavements, bridges, railways, airports, dams, embankments, towers, coastal infrastructure, and other structures (2–10). Close-range

photogrammetry (CRP) is the science of making measurements remotely from two or more images collected using a camera sensor placed within shorter distances from the object (11–15). The availability of several commercial flight-planning and photogrammetric software packages has also proliferated the use of drones for

¹Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI

²Bridge Design Division, Alaska Department of Transportation & Public Facilities (Alaska DOT & PF), Juneau, Alaska

³Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX

Corresponding Author:

Surya Sarat Chandra Congress, surya@msu.edu

remotely gathering information for qualitative and quantitative assessments.

In the past few years, there has been a steady increase in the application of UAVs for conducting bridge inspections owing to their ability to safely access hard-to-reach areas. Although UAVs with current configurations are not expected to replace the arm's length inspections, the low maintenance and mobilization costs of UAVs along with the development of high-quality compact sensors have provided the impetus for conducting the preliminary visual monitoring of bridges. These inspection assessments can provide the details necessary to plan any further in-depth inspections.

Many previous studies have accomplished bridge deck inspections using infrared, optical images, and also three-dimensional (3D) models (4, 6, 8, 16). The 3D mapping of a bridge deck is similar to that of horizontal planar surfaces such as pavements, which was conducted by various studies (17–19). However, not many studies have reported the 3D reconstruction of the under-span of a bridge and its limitations. Besides, none of these studies reported developing 360° bridge models and using them to provide an immersive experience to the bridge inspector. The 360° bridge models are essentially digital replicas depicting the existing conditions of bridges. They can provide the visuals of the super- and sub-structures of a bridge. Moreover, they also offer the benefit of associating images with the bridge elements in the 360° models.

The authors collaborated with 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 three bridges using optical and infrared imagery. Each bridge was selected to represent a wide range of bridge types and conditions, therefore several key observations for each bridge were included for a better understanding. Optical images were used to build 3D models of all bridges, and infrared images were also used to conduct a qualitative inspection of a bridge and understand the influence of thermal loading in depicting distress conditions. Some of the key observations for data collection and processing of UAV data were highlighted in the conclusions.

Background

Bridge Inspections

Bridge inspections in the U.S. are conducted based on the National Bridge Inspection Standards (NBIS). The American Association of State Highway and

Transportation Officials (AASHTO) Transportation Glossary (20) defines a bridge as

a structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having an opening measured along the center of the roadways of more than 20 feet between undercopings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening.

Inspection Types

Bridge inspection is largely a visual process. Inspection programs for both federal and state-owned bridges follow the definitions and guidelines provided in the NBIS. It also establishes federal regulations for inspection procedures, frequency of inspections, qualification of personnel, inspection reports, and maintenance of bridge inventory. Table 1 and Figure 1 list the details of seven types of bridge inspections defined by NBIS (20).

Traditional Equipment

The Federal Highway Administration (FHWA) Bridge Inspector's Reference Manual divides the tools needed during an inspection into two broad groups: standard tools and special equipment (21), as shown in Table 2.

Uncrewed Aerial Vehicle-Based Inspections

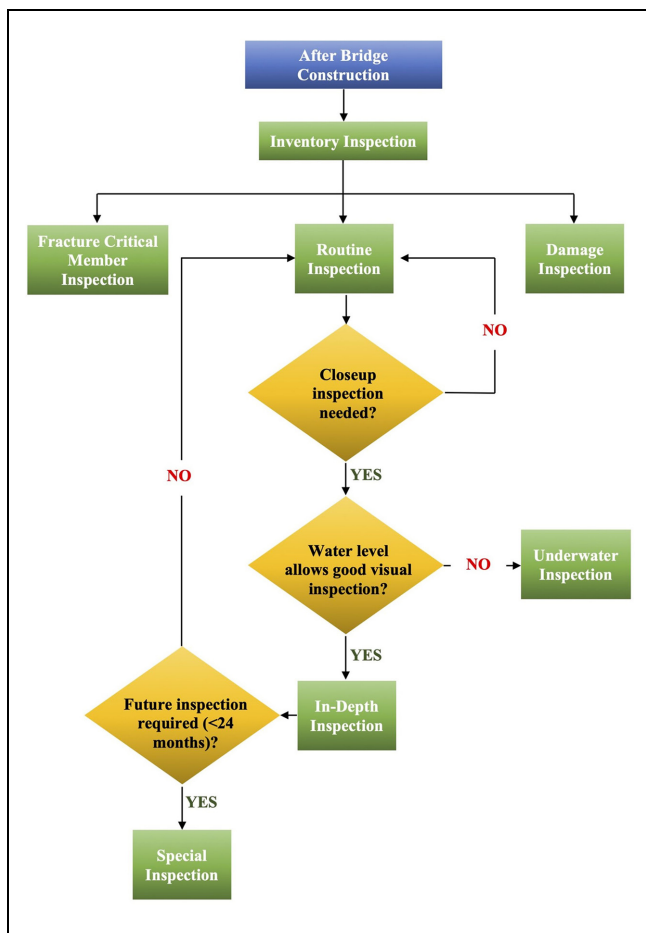
Several departments of transportation agencies have started using UAVs for conducting bridge inspections. Some of those studies are provided below:

Michigan Department of Transportation conducted a study to evaluate the application of UAVs for pavements and bridges using different sensors (4). 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 (22). 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 identified major bridge reporting categories and provided a scale to rate the usefulness of UAVs for bridge inspections (23).

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 (3). They were

Table 1. Bridge Inspection Types (20)

Inspection category	Definitions
Inventory inspection	The first inspection of a bridge as it becomes a part of the bridge file to provide all Structure Inventory and Appraisal (SI&A) data and other relevant data and to determine baseline structural conditions.
Routine inspection	A regularly scheduled inspection consisting of observations, measurements, or both is performed to determine the physical and functional conditions of the bridge to identify any changes from initial or previously recorded conditions and to ensure that the structure continues to satisfy present service requirements. The inspection will not exceed a frequency of 24 months.
Damage inspection	An unscheduled inspection to assess structural damage resulting from environmental factors or human actions.
Special inspection	An inspection is scheduled, at the discretion of the bridge owner, to monitor a particular known or suspected deficiency.
In-depth inspection	A close-up inspection of one or more members above or below the water level is performed to identify any deficiencies not readily detectable using routine inspection procedures; hands-on inspection may be necessary at some locations.
Fracture critical member (FCM) inspection	A hands-on inspection of a fracture critical member or member components that may include visual and other nondestructive evaluation. An FCM is defined as a steel member in tension, or with a tension element, whose failure would probably cause a portion of or the entire bridge to collapse. The inspection will not exceed a frequency of 24 months.
Underwater inspection	An inspection of the underwater portion of a bridge sub-structure and the surrounding channel, which cannot be inspected visually at low water by wading or probing, generally requiring diving or other appropriate techniques.

**Figure 1.** Bridge inspection types.

able to demonstrate a 360° inspection of a bridge section. Some of the lessons learned from that study helped us to conduct the present study (24). An implementation project was also conducted to validate the TxDOT UAV systems flight operations manual developed in the preceding research project. Communication towers, high mast tower, intersections, building, and bridge were initially considered for UAV-based inspections (25). North Carolina Department of Transportation 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 (26). These often affect 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 (sUAVs) 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. 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 from FDOT was present to evaluate the effectiveness of the aerial inspection using UAV. The study authors 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

Table 2. Traditional Equipment used for Bridge Inspection (21)

S. No.	Category of tools	Inspection equipment
Standard tools		
1.	Cleaning	Whisk brooms, wire brushes, etc.
2.	Visual aid	Binoculars, flashlights, mirrors, etc.
3.	Inspection	Pocket knives, ice picks, timber boring tools, etc.
4.	Measurement	Pocket tape, level, ultrasonic thickness gauge, etc.
5.	Documentation	Inspection forms, notebooks, camera, etc.
6.	Access	Ladders, boats, rope, bucket trucks, etc.
7.	Miscellaneous	Clamps, first aid kit, insect repellent, etc.
Special equipment		
1.	Survey equipment	Transit, level, incremental rod, etc.
2.	Nondestructive evaluation	Sonic testing device, spectral analysis, ultrasonic testing, etc.
3.	Underwater inspection	Diving equipment, sounding equipment, etc.
4.	Other special equipment	Air-water jet, sandblasting, burning, drilling equipment, etc.

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 (27).

Because of 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, the authors reported some difficulty in capturing the top surface of the bottom flange of steel girders because of 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 spacings resulted in low light conditions, whereas bridges with high clearances generated more wind gusts (27). A recent study funded by FHWA also mentioned about the use of orthorectified images for quantitative inspections of the bridge elements. The investigators magnified, cropped, and scaled an aerial image and overlaid it on the bridge plans to make measurements without the help of ground control points (28).

Current Challenges to 360° Bridge Inspections

Bridges, unlike other structures, offer several unique challenges for conducting inspections. Although 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. In part, this 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 because of the wind conditions and the unreliability of the relatively poor/distorted views provided by the first-person view 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 following sections.

Methodology for 360° Bridge Inspections

A data-collection team consisting of multiple Federal Aviation Administration (FAA)-certified drone remote pilots in command (RPICs) and visual observers (VOs) can be used based on the complexity of the airspace and inspection activities. Various UAV platforms equipped with optical cameras can be deployed for mapping the super- and sub-structure elements of the bridges. The obstacle sensors on the drones can be helpful while inspecting the bridge elements; however, caution must be exercised while operating the drones near tree twigs and closer inner spaces under the bridge deck. Further, infrared camera sensors can be used for qualitative inspection of bridges. Some of the important steps involved in

planning, collection, and processing of aerial data are outlined and pictographically depicted below.

Coordination and Data Collection

Planning and Reconnaissance. Planning of aerial inspections can be conducted after studying the bridge plans and previous inspection reports. Further, the inspection task objectives can be laid out with the help of the bridge inspector.

- Traffic directions and allowable speeds on the bridges can be accounted for to identify preliminary take-off and landing spots, RPIC positions, and VO positions.
- The number of flights and inspection time can be roughly assessed based on the sensor specifications, required detail, and surface area of the bridge elements.
- During the day of data collection:
 - Site reconnaissance can be conducted to identify any potential obstructions to the planned manual and automated flights.
 - It is crucial to account for unfavorable conditions that may not have been identified during the online reconnaissance and amend the flight plans accordingly.
 - A safety briefing can be held to communicate the inspection objectives to the data-collection team.
 - The positions of the VOs and the connectivity of the walkie-talkies/hands-free headsets can be verified.
 - The data-collection team members can also be instructed about the measures to be followed in areas with potential wildlife interactions.
 - The equipment can be set up and tested before flying over the actual assets. Appropriate safety guidelines need to be followed. In this study, data collection was conducted as per FAA Part 107 guidelines.

360° Bridge Inspection. The 360° inspection of each bridge can be conducted by dividing the field operations into three stages, as shown in typical image locations on the 3D models in Figure 2, *a* to *f*. First, the bridge deck can be mapped using nadir images with a minimum of 80 percent overlap (Figure 2*a*). Second, the oblique images of the bridge can be captured on both sides (Figure 2*b*). Third, the images of the under-bridge spans (Figure 2*c*), pier caps (Figure 2*d*), pier verticals (Figure 2*e*), and abutments (Figure 2*f*) can be captured. Automated flight missions can be conducted during the first stage,

unless challenged by obstructions, and manual flight missions can be conducted for the rest of the bridge inspections.

It should be noted that the UAVs were not flown over moving vehicles as part of the inspections conducted in this study. The flight characteristics and paths were planned outside of the travel lanes. In unavoidable cases, where the UAV was flown over travel lanes (for a minimal time) to achieve the required overlap, two VOs, each equipped with long-range radios, were placed at a safe distance away from both ends of the bridge to communicate with the drone RPIC. When the drone approached the travel lanes, the VOs communicated about any approaching vehicle and also the description of the vehicle after which there will be a gap in the traffic flow. When there is incoming traffic, the RPIC paused the flight plan and flew the UAV away from the travel lanes before resuming the flight plan during the gap in the traffic flow.

Data Processing and Analysis

In this study, the aerial images of the bridges were processed using a Windows 64-bit operating system with Intel® Xeon® Gold 6148 CPU with 2.40°GHz, 192 GB RAM, and two NVIDIA V100 GPUs to generate a mesh, render texture, and orthomosaics for the bridges.

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. An orthomosaic is a map generated by using the mesh model and 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. Mostly, a typical data-processing and model-generation workflow was followed in generating the 3D mapping products (29). Some additional steps can be performed to accomplish 360° inspections as outlined below:

- The orthomosaic of the bridge deck can be obtained by disabling the under-bridge images and processing the deck images using a pre-defined coordinate system. The near end (NE) and far end (FE) of each bridge can be marked in the bridge deck orthomosaics.
- The orthomosaic of the under-bridge span can be generated by following these steps: (1) disabling the deck and oblique 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 to avoid the ground.
- Similarly, the orthomosaic of each bridge side can be generated by changing the view direction and

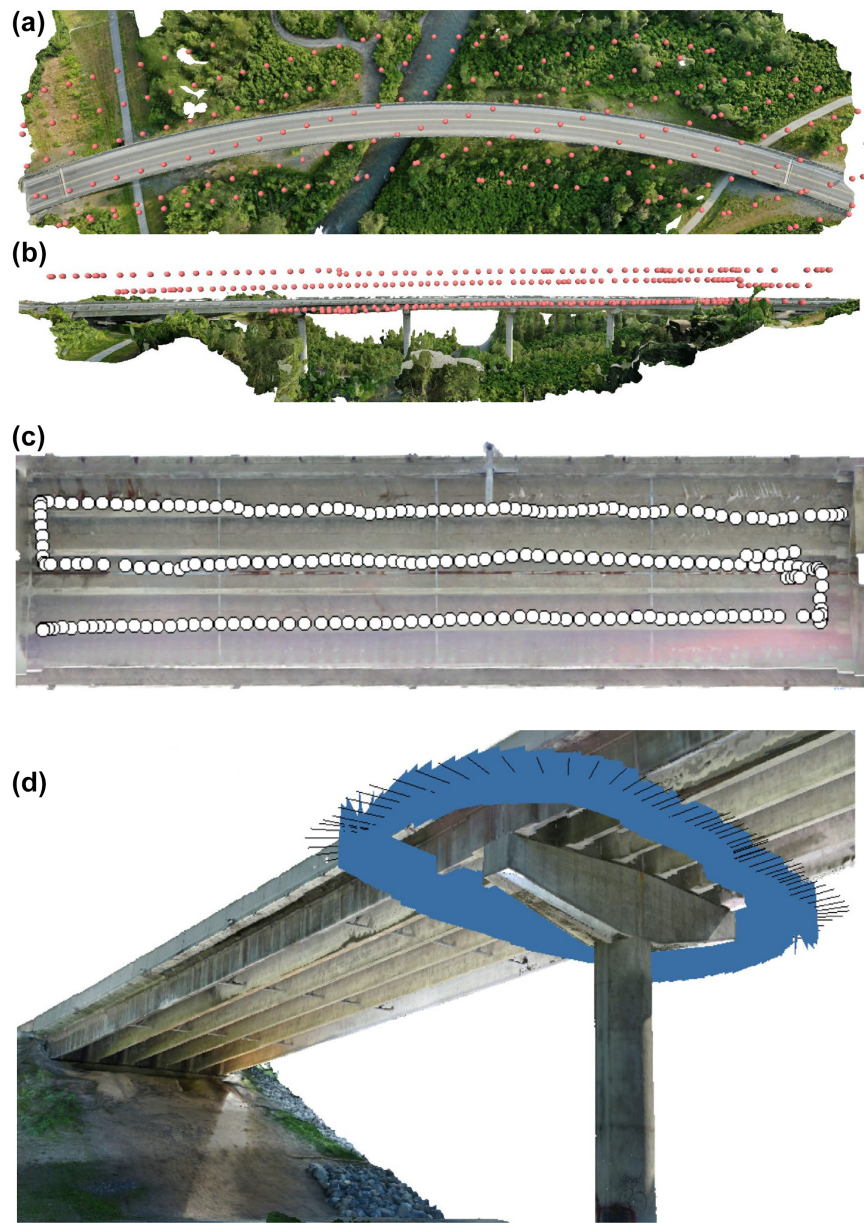


Figure 2. (continued)

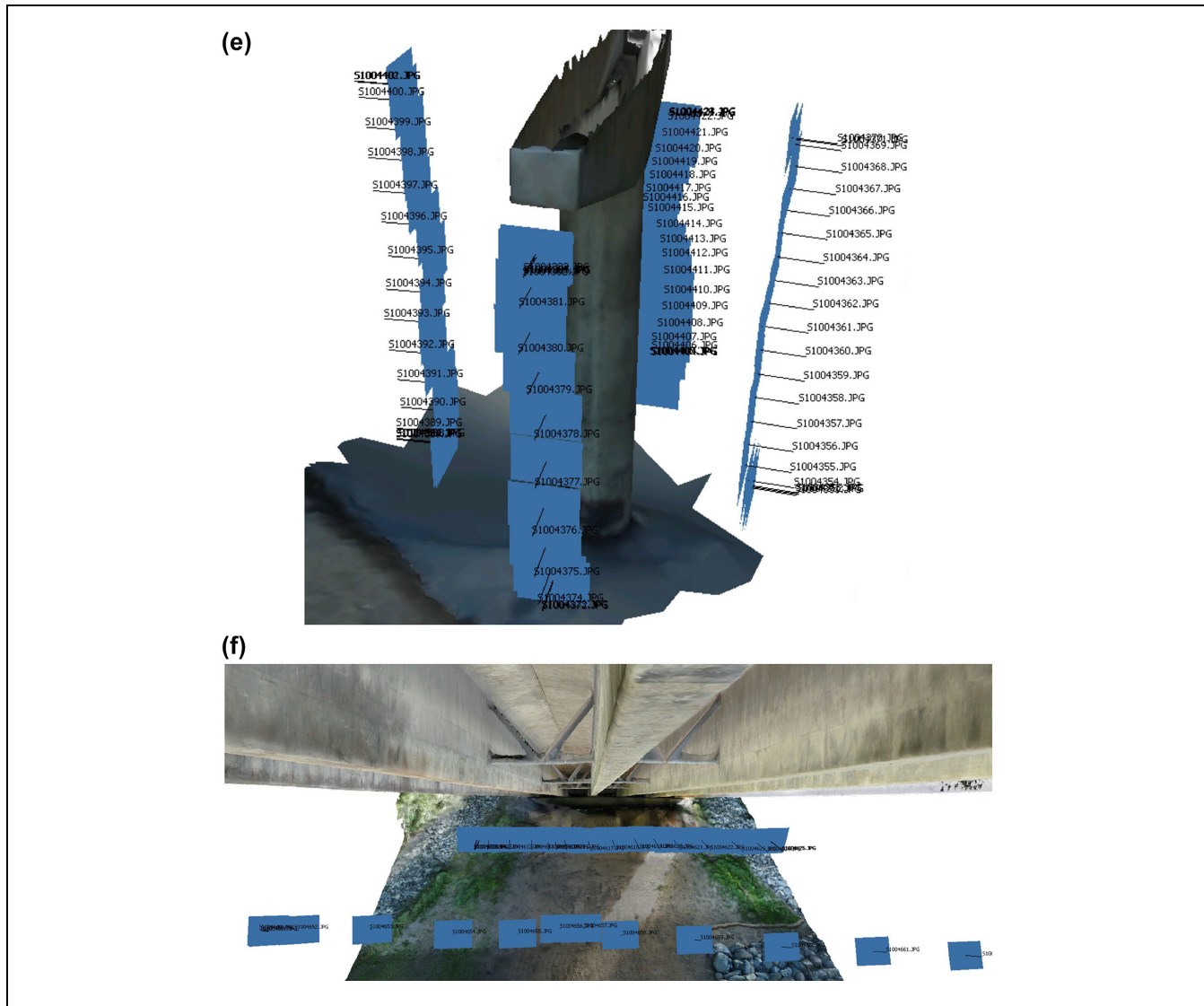


Figure 2. Typical uncrewed aerial vehicle flight paths: (a) first stage: nadir flights, (b) second stage: oblique flights, (c) third stage: under spans, (d) third stage: pier cap, (e) third stage: pier verticals, and (f) third stage: abutment.

disabling the images capturing the bridge elements other than those on the bridge side under reconstruction.

The 360° bridge models can be built and an orthomosaic, a single stitched image, of each of the four sides of the bridge can be provided to the bridge engineer. The advantage of generating an orthomosaic is that they allow zooming into a single picture while preserving the quality of the original images. Further, the bridge inspector can scale those high-quality orthomosaics with the help of existing bridge designs in AutoCAD software or other software to quantify the distress conditions.

Oftentimes, the bridge inspectors may not get these detailed views of the bridge structure while conducting a

routine inspection using traditional methods. From a bridge engineer/inspector's perspective, the high-resolution orthomosaics are very useful from a data-collection, tracking, and recording perspective as they can be used as a snapshot in time that can be recreated at a different point in time for comparing and tracking the growth of multiple surface-level defects, which may not be easily obtained from traditional routine inspections. This methodology was demonstrated for 360° bridge inspections of the below case studies.

Case Studies on 360° Bridge Inspections

The methodology developed in this study was demonstrated on three case studies attempting to conduct 360°

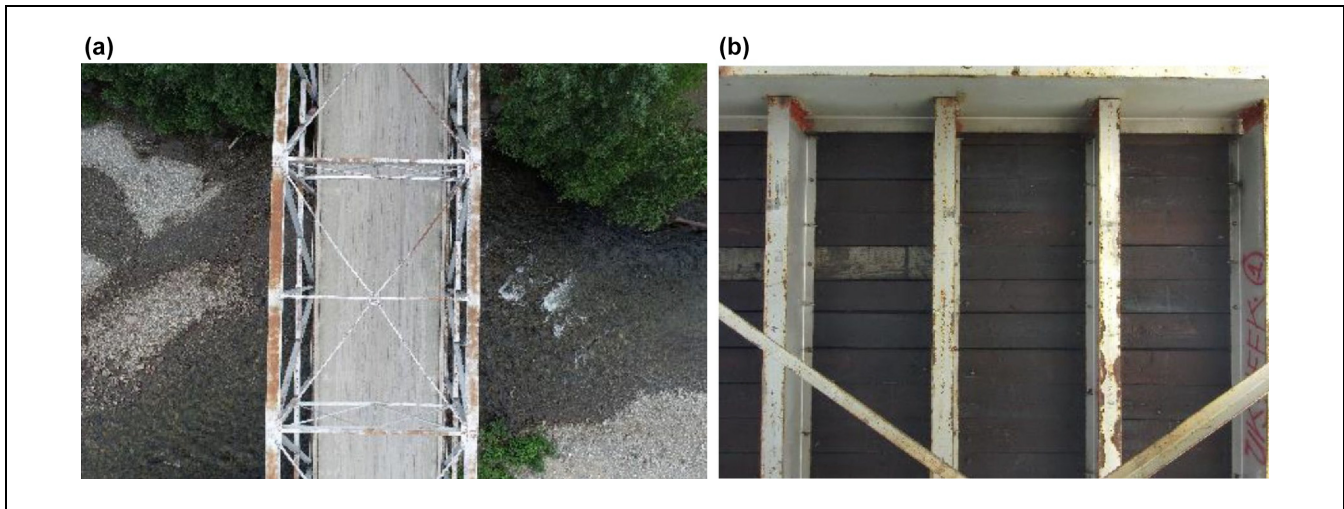


Figure 3. Aerial inspection of the 1669 bridge elements: (a) nadir view of super-structure and (b) bottom up view of under-span.

inspection of bridges, Montana Creek Bridge, Canyon Creek Pedestrian Bridge, and Eagle River Southbound Bridge, located in Alaska. The terrains in rural areas pose a unique set of logistical challenges because of remoteness and lack of network connectivity for conducting UAV-based inspections of bridges. The workflow developed in this study was key to performing the inspections without any logistical delays caused by the unavailability of internet or cell network coverage.

Montana Creek Bridge (1669)

Bridge Details. This is a steel-truss bridge with a timber deck built in 1988. It has a 205 ft-long and 28 ft-wide bridge deck supported on two abutments. It is located on Yoder Road near Talkeetna, Alaska. The bridge deck serves as an undivided two-lane road. The west end of the bridge connects the road toward Talkeetna and the east end connects the road to Susitna North. The areas surrounding the bridge abutment on the east side are densely vegetated. The vertical clearance from the level of the stream to the bridge deck was relatively at maximum (~5 to 10 ft) because of a small flow of water. However, this clearance is considered low for operating most industrial-grade drones commercially available in the market. Therefore, a small drone that predominantly works on using vision sensors to avoid obstacles was used for under-bridge inspections conducted in this study.

Aerial Inspection Highlights. The bridge abutment areas were accessed on both sides by walking on the bridge deck. It has low annual average daily traffic so the data-collection team neither stopped the traffic nor parked on the bridge deck. Simultaneous drone operations, using

multiple drones operated by multiple RPICs and VOs, were conducted to inspect the super-structure elements of the bridge (Figure 3). It took approximately two and a half hours (~2.5 h) to collect a total of 1631 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 by the movement of the ground vehicular traffic, which was provided the right of way throughout the UAV-based inspections.

It took approximately seventeen hours (~17 h) to process the aerial imagery and generate mesh models having a total data size of 775 megabytes (MB). It should be noted that, depending on the bridge types and the complexity of the terrain, 80%–90% of this time is used by automated processes. The orthomosaics of the bridge deck, under-span, and both side faces having a total data size of 55 MB were generated as shown in Figure 4. It can be observed that there is a 93% reduction in data-storage requirements when storing and using orthomosaics instead of 3D models, although the latter was used to generate the former datasets. The viewpoint of the 3D model, shown in Figure 5a, is indicated by the maroon arrow shown in Figure 4a. The left and right sides of the under-bridge span orthomosaic, shown in Figure 4b, indicate the Talkeetna (NE) and End of Yoder Road (FE) sides of the bridge, respectively. The close-up view of the area marked by a red rectangle on the under-span orthomosaic indicates the quality of the aerial data. The orthomosaics of the north and south sides of the bridge are shown in Figure 4, c and d, respectively. The conditions of the gusset plates, joints, rivets, paint peeling, and rusting can be observed in Figure 4. The three-dimensional views shown in Figure 5 also help in identifying their conditions.

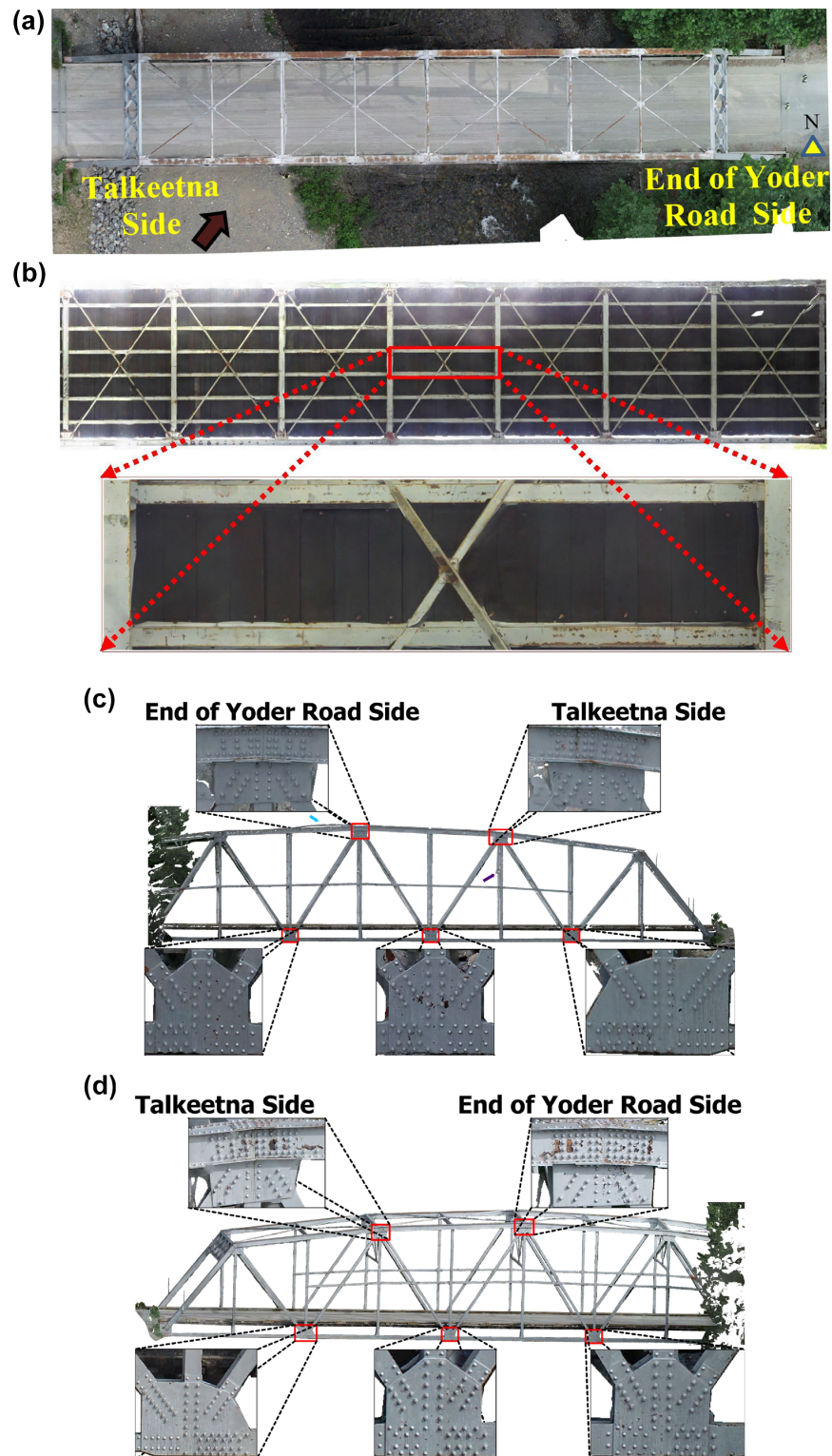


Figure 4. 360° inspection of Montana Creek Bridge: (a) deck, (b) under-span, (c) north face, and (d) south face.

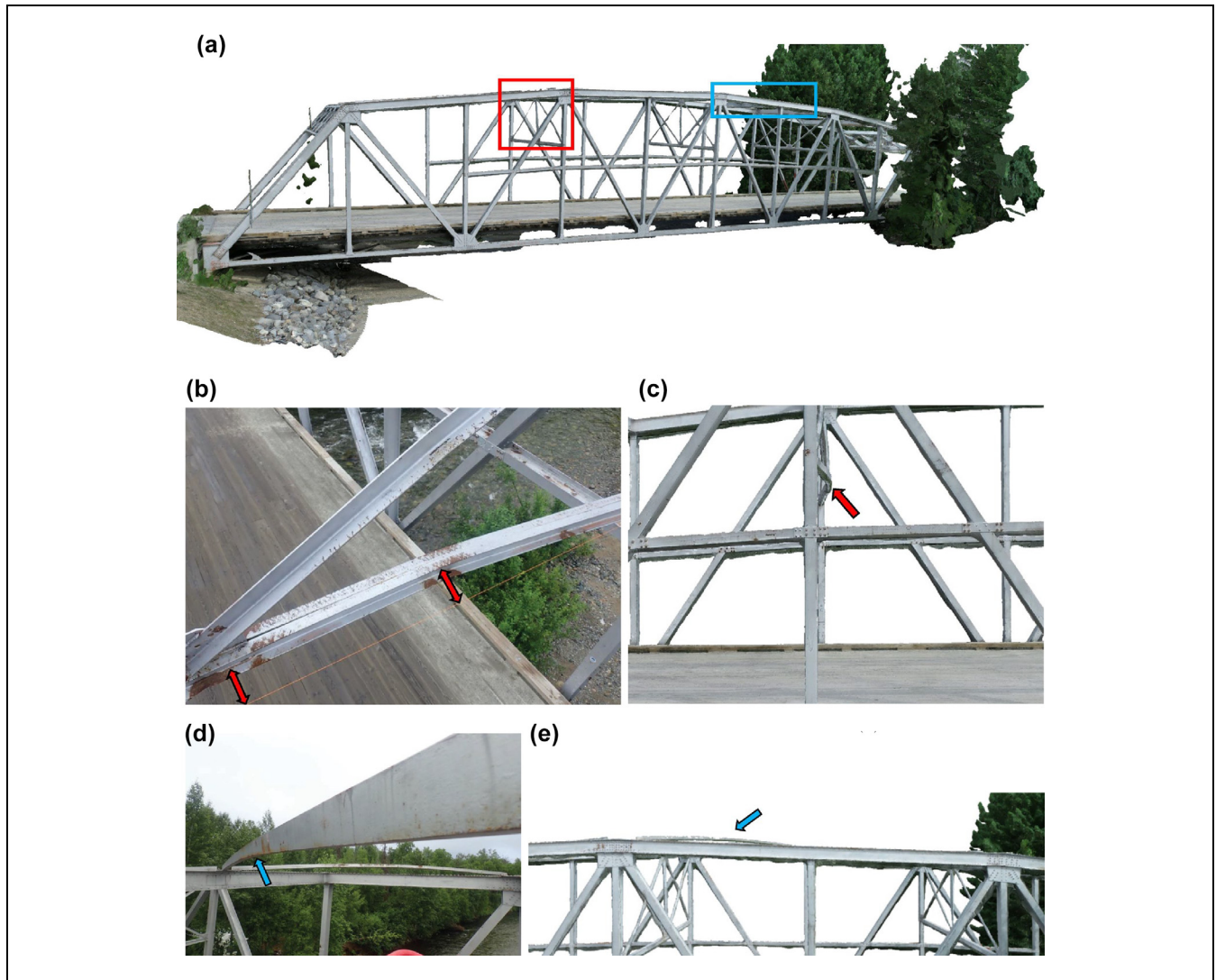


Figure 5. Montana Creek Bridge condition assessments: (a) 3D model viewed from the southwest direction, (b) bent U3 sway bracing viewed from the west during fracture critical inspections in 2020, (c) bent U3 sway bracing in the 3D model viewed from the south, (d) bowed U5-U4' top bracing viewed from the north during fracture critical inspections in 2020, (e) bowed U5-U4' top bracing in the 3D model viewed from the south.

Condition Assessments. The high-resolution 3D models and orthomosaics generated from the aerial imagery were able to provide ways to examine the corroded areas, bent truss elements, debris accumulation, condition of the timber ties, and clearance available for vehicles to pass. Under traditional inspections, some of these assessments would require a crane and intermittent closure of the bridge for traffic. The routine bridge inspection report prepared by Alaska DOT&PF in 2020 was accessed to make a comparison with the aerial imagery and 3D models. Some of the assessments identified in both inspections are cracking on the bridge approach asphalt surfaces, paint peeling on gusset plates, bent sway bracing, bowed top bracings, bullet holes on the

elements, debris accumulation on the lower chords, rusting on multiple bridge elements, paint loss and minor pitting on the bearings.

The magnitudes of U3 sway bracing and U5-U4' top bracing measured using crew-up equipment as part of the traditional fracture critical member (FCM) inspections conducted by Alaska DOT&PF in 2020 can be observed in Figure 5, *b* and *d*, respectively. The close-up view of the bent sway bracing, indicated by the purple arrow in Figure 4*c* and the red rectangle in Figure 5*a*, can be observed in the 3D model shown in Figure 5*c*. The close-up view of the bowed top bracing, indicated by the blue arrow in Figure 4*c* and the blue rectangle in Figure 5*a*, can be observed in the 3D model shown in Figure 5*e*.

Key Observations. Although the objective of this bridge inspection was to create a single 3D model of the whole bridge, the research team processed them separately for two reasons:

- (1) While operating underneath the bridge, during the third stage of data collection, the increase in brightness settings of the camera to counter the shadows, created by the low clearance and cloudy conditions, provided unrealistic and disparate views of the same features captured during the other two stages of data collection.
- (2) Owing to the above reason, excessive manual inputs, that is, tie points, need to be provided to assist the photogrammetric software in stitching the adjacent images. This may not always be practically feasible for a bridge inspector. In photogrammetry processing techniques, a tie point represents the same location in two or more images and is used to stitch the 2D images and build 3D models.

These models and orthomosaics are still helpful, as one of the common problems while conducting the bridge under-span inspections is the loss of context for the image caused by two reasons, (1) unreliable GPS connection and (2) similarity between elements which are inspected closely without having much background information. Therefore, the models offer context and the ability to retrieve high-quality images to further inspect the bridge elements' conditions. The experience gained in processing the aerial imagery of this bridge was helpful in accomplishing 360° models for the other bridges as outlined below.

Canyon Creek Pedestrian Bridge (6020)

Bridge Details. This is a steel girder bridge built in 1950 with reinforced concrete deck material and asphalt wear surface. It used to cater to vehicular traffic before construction of another bridge in 1997 that turned this into a pedestrian bridge. It has a 290-ft-long and 30-ft-wide bridge deck supported by four piers along five spans in between the abutments. It is located on Old Seward Highway near Hope, Alaska. Except for the fourth and fifth spans (counted from the southeast side of the bridge), all other areas surrounding this bridge are densely vegetated on either side of the stream, which is flowing from southwest to northeast under the fourth span (Figure 6). Unlike the Montana Creek Bridge, this bridge has adequate clearance above the stream.

Aerial Inspection Highlights. Three stages of data collection were conducted to inspect the bridge deck, the fourth

under-span, and the piers. Attempts to inspect the other bridge elements were hindered by the presence of dense vegetation, as can be observed in Figure 6. The high clearance and the weather conditions assisted in capturing the bridge elements with similar views in all three stages. It took approximately two and a half hours (~2.5 h) to collect a total of 1,106 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 as a result of the movement of pedestrians, who were provided the right of way throughout the UAV-based inspections. This along with the high overlap between images particularly helped in ensuring minimal manual effort and maximum utilization of the photogrammetric software for automatic estimation of tie points between adjacent images. A single 3D model was built for conducting a 360° inspection of the bridge.

It took approximately eighteen hours (~18 h) to process the aerial imagery and generate mesh models having a total data size of 1.39 gigabytes (GB). The orthomosaics of the bridge deck, fourth under-span, and both side faces having a total data size of 32 MB were generated as shown in Figure 7. It can be observed that there is a 97% reduction in data-storage requirements when storing and using orthomosaics instead of 3D models. The viewpoint of the 3D model is indicated by the maroon arrow shown in Figure 7a. The red rectangle in Figure 7a indicates the area covering the fourth under-span. The orthomosaic of the under-bridge span, with the left and right corners of the image indicating the Anchorage (NE) and Seward (FE) sides of the span, respectively, is shown in Figure 7b. The close-up view of the area marked by a red rectangle on the under-span orthomosaic provides a detailed scaled view of the area. The orthomosaics of the north and south sides of the bridge are shown in Figure 7, c and d, respectively. Dense vegetation around the bridge can be observed to hinder the visibility of the bridge elements and their inspection. The condition of the patchwork and the salts coming through the cracks can be observed in Figure 7.

Condition Assessments. The 360° bridge model can be observed to depict the conditions of under-bridge elements and the abutment slopes shown in Figure 8, a and b. The routine bridge inspection report prepared for this bridge by Alaska DOT&PF in 2017 was accessed to make a comparison with the aerial imagery and 3D models. Some of the assessments identified in both inspections are spalled curbs, rusting, paint peeling, efflorescence staining, bearing conditions, and potential abutment erosion.

The conditions of the bearings were inspected closely during the uncrewed aerial inspections as shown in

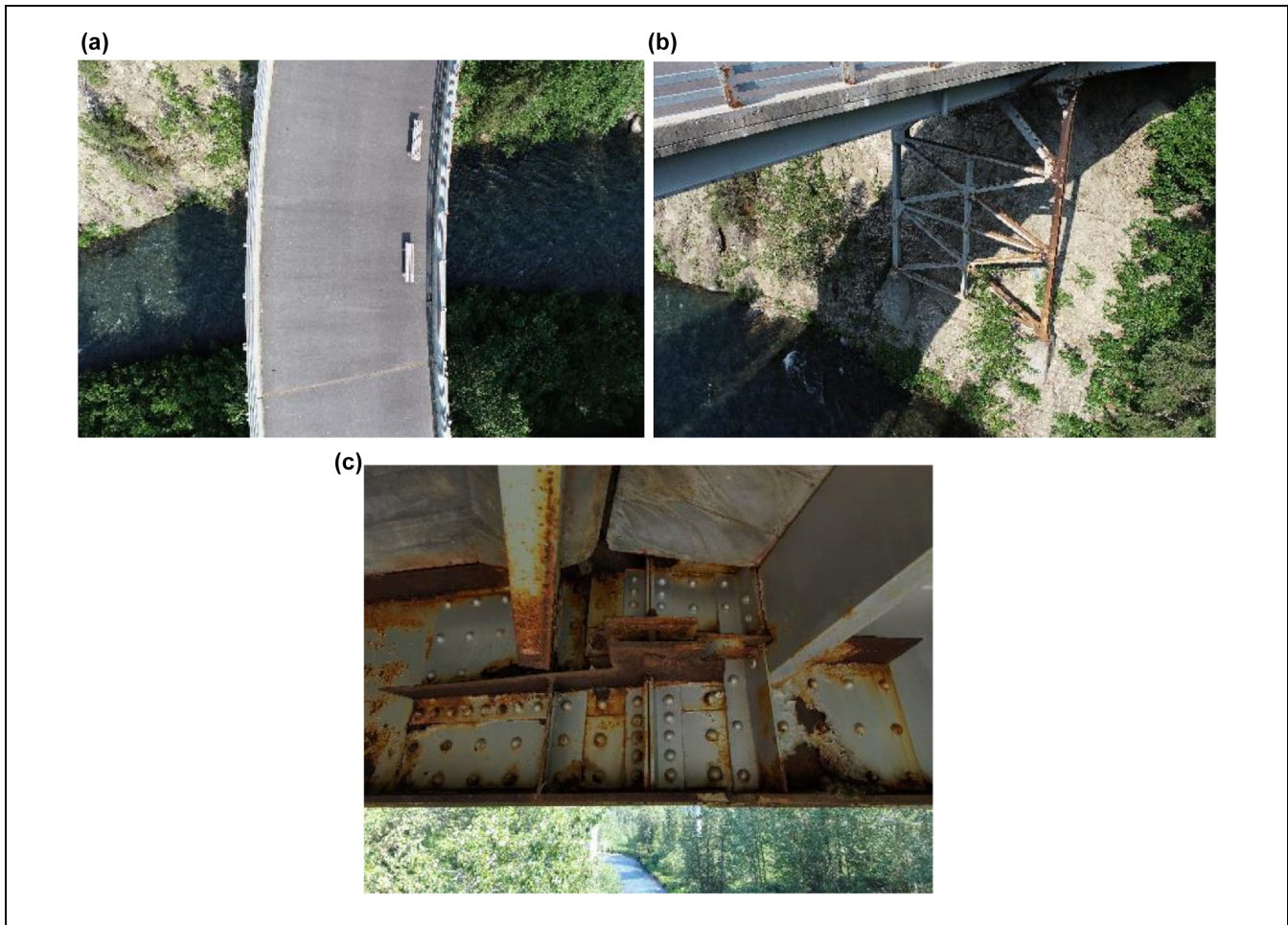


Figure 6. Aerial inspection of the 6020 bridge elements: (a) nadir view of super-structure, (b) top down oblique view, and (c) oblique view of under-span in bottom up direction.

Figure 8, *c* and *d*. The shadows can be removed, and the lighting conditions can be enhanced during post-processing (Figure 8*e*). The condition of the joint sealant near under-span 4 can be seen in Figure 8*f*. All these images were able to depict the rust, paint peeling, and debris conditions of the under-bridge elements.

Key Observations

- The ability to launch the drone from the hand for conducting under-bridge inspections was extremely useful on terrain with uneven surfaces and loose dirt conditions.
- There was no interference experienced by the UAV while closely inspecting the steel members. The ability to fly in close spaces with vision-based obstacle avoidance sensors to inspect the conditions of under-bridge elements was very helpful.
- The presence of dense vegetation prevented inspection of the other under-bridge spans; however,

routine inspection with traditional practices such as using binoculars would have faced the same issue with obscured views.

Eagle River Southbound Bridge (1341)

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 toward 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

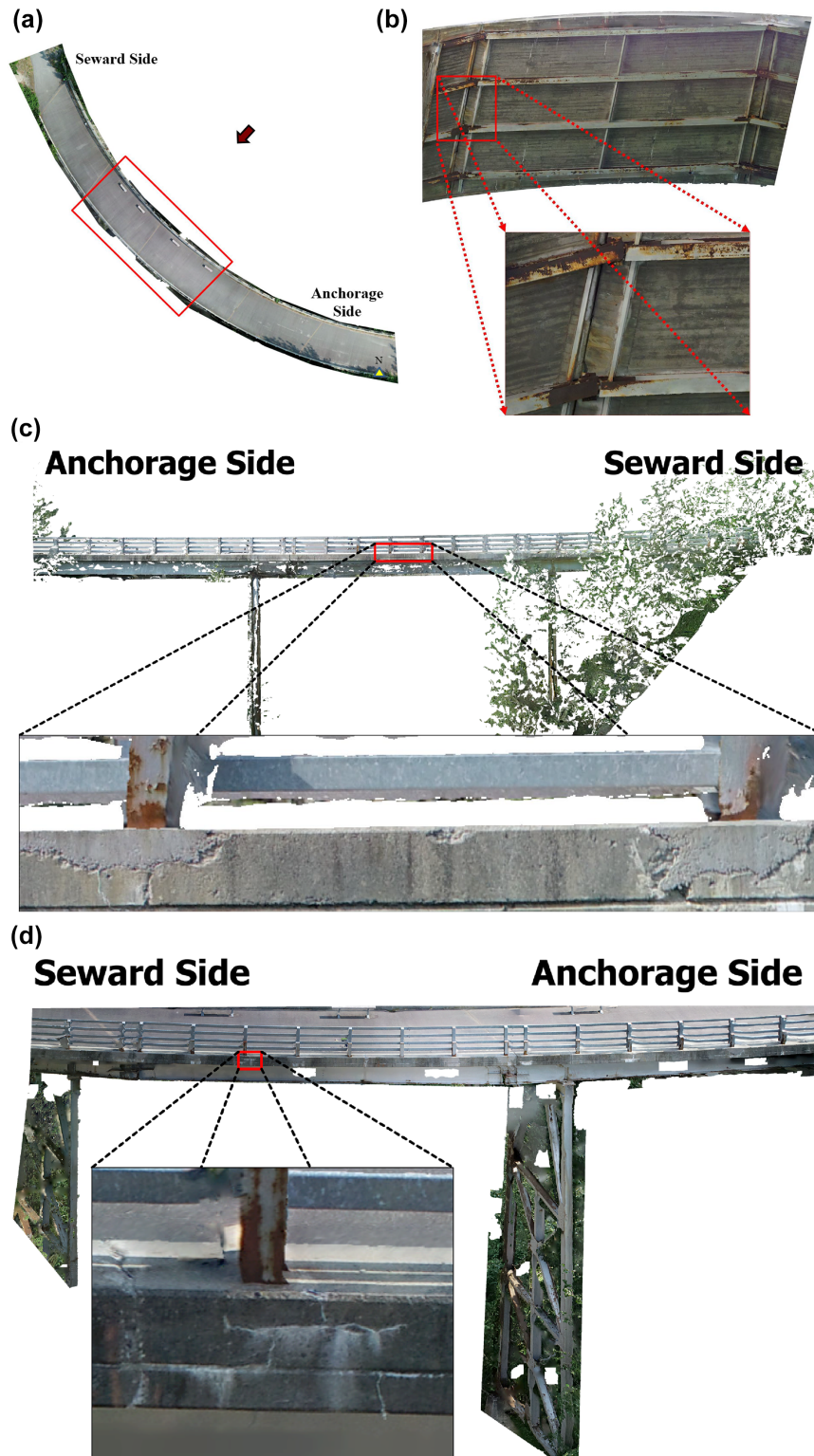


Figure 7. 360° inspection of Canyon Creek Pedestrian Bridge: (a) deck, (b) under-span, (c) north face, and (d) south face.



Figure 8. Canyon Creek Pedestrian Bridge condition assessments: (a) 3D model viewed from the northeast direction, (b) 3D model viewed from underneath the fourth span, (c) bearing condition, (d) close-up view of the bearing, (e) enhanced image, and (f) joint sealant condition.

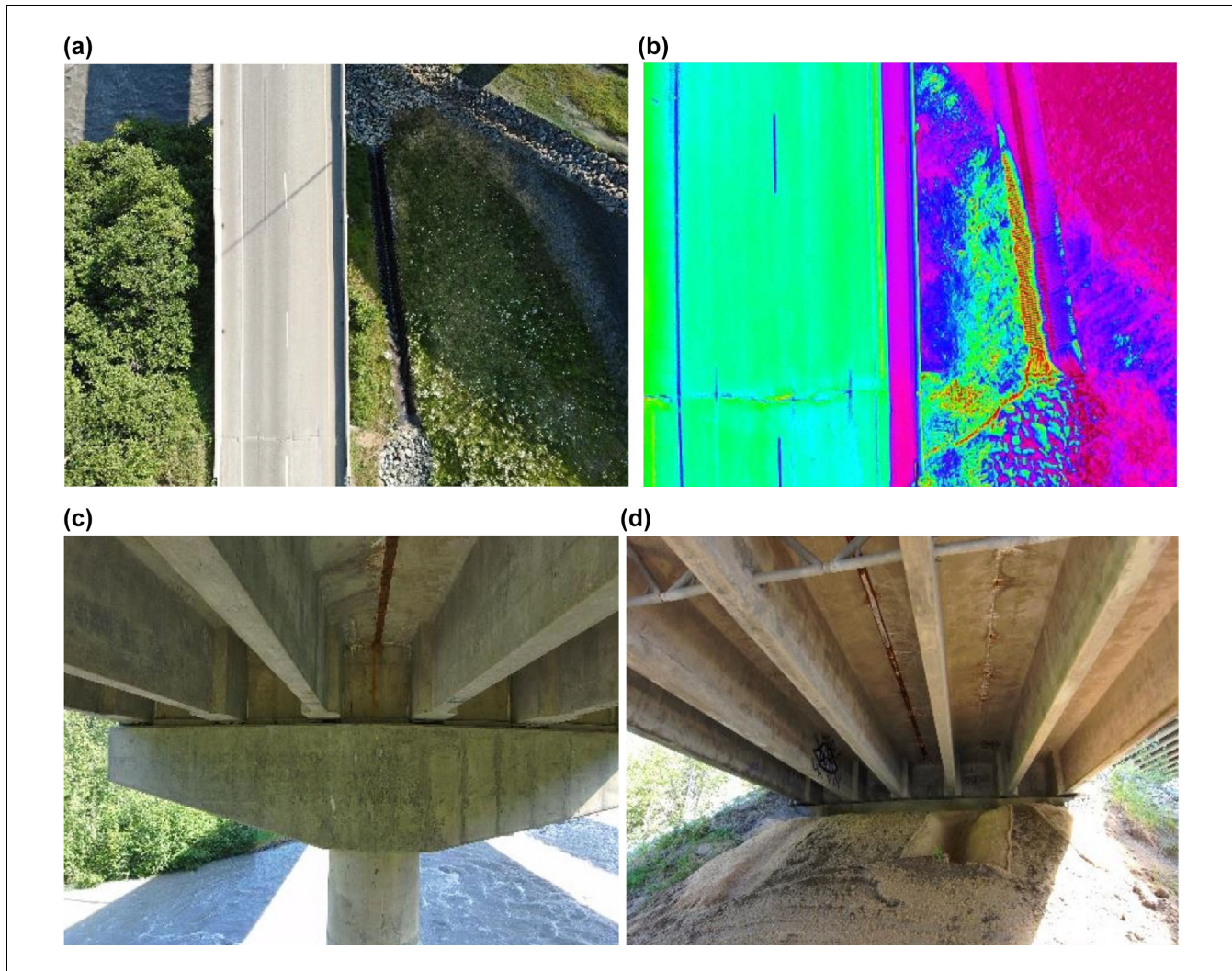


Figure 9. Aerial inspection of the I341 bridge elements: (a) RGB image of bridge deck, (b) infrared image of bridge deck, (c) aerial inspection of pier cap, and (d) aerial inspection of abutment on Palmer side.

Survey, the areas surrounding this bridge experienced an earthquake of magnitude 7.1 in 2018.

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 h) to collect a total of 1,624 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 because of 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 9.

It took approximately sixteen hours (~16 h) 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 10. It can be observed that there is a 93% reduction in data-storage requirements when storing and using orthomosaics instead of 3D models. The viewpoint of the 3D model, shown in Figure 11a, is indicated by the maroon

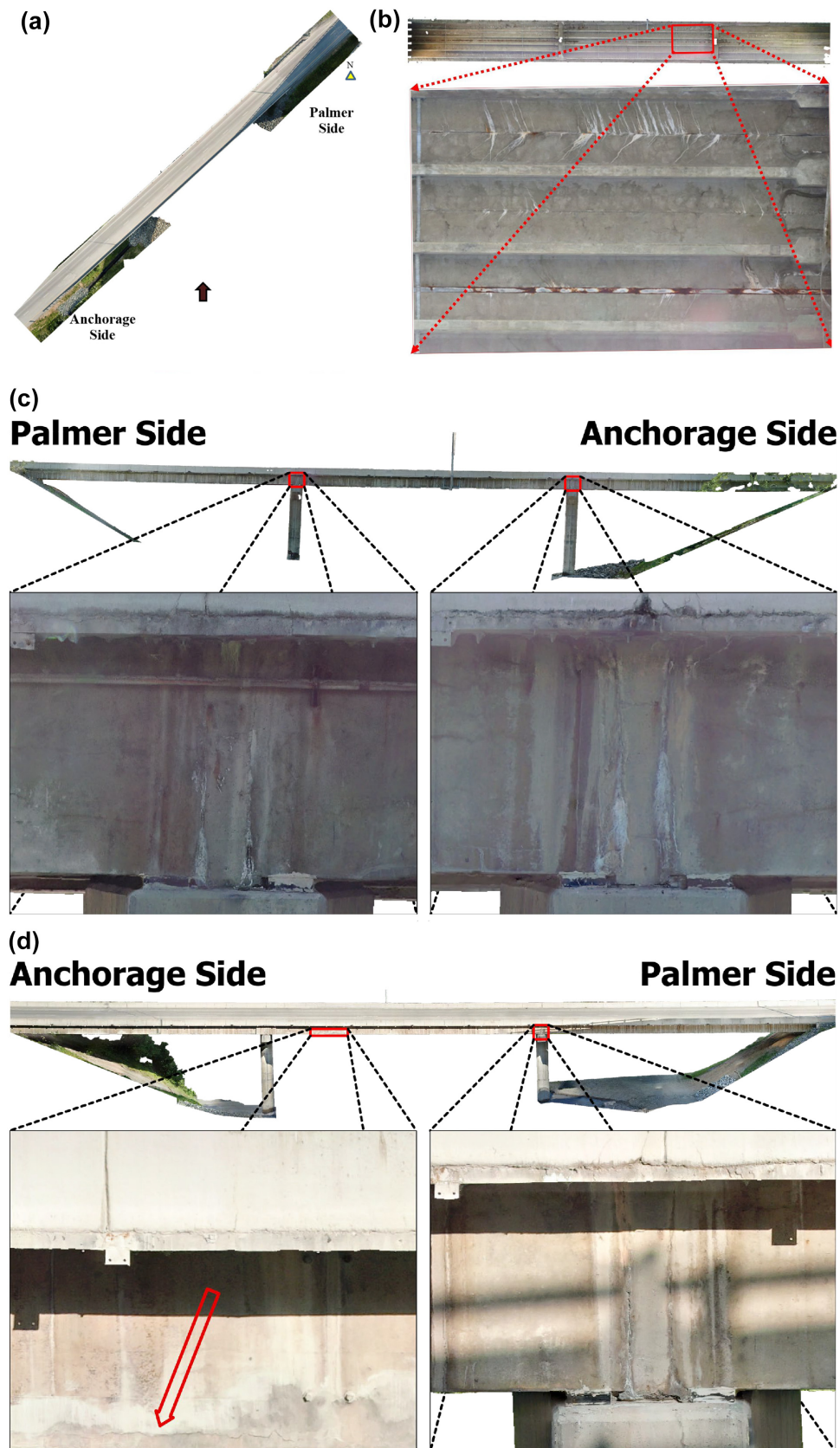


Figure 10. 360° inspection of Eagle River Southbound Bridge: (a) deck, (b) under-span, (c) north face, and (d) south face.

arrow shown in Figure 10*a*. The left and right sides of the under-bridge span orthomosaic, shown in Figure 10*b*, indicate the Anchorage (NE) and Palmer (FE) sides of the bridge, respectively. The close-up view of the area marked by a red rectangle on the under-span orthomosaic provides a detailed scaled view of the under-span. The orthomosaics of the north and south sides of the bridge are shown in Figure 10, *c* and *d*, respectively. The conditions of the girders, pier caps, bearings, and other bridge fascia elements were inspected.

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 11. 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 10*b*. Rail-end spalling and exposed reinforcement identified during the traditional routine inspections in 2019 can be observed in Figure 11*b*. The same distress can be observed in both the aerial RGB image and the 3D model shown in Figure 11, *c* and *d*, respectively. The asphalt crack formed as a result of the 2018 earthquake can also be observed in Figure 11*d*. Cracks, formed as a result of patchwork, can be observed in both infrared and optical images shown in Figure 11, *e* and *f*, respectively.

The importance of the thermal loading and its angle of incidence for the identification of cracks, formed as a result of formwork, can be observed from the inability to distinguish cracks in infrared images, even though they are visible in optical images shown in Figure 11, *g* to *j*. Concrete falloff near the patched area on the south face girder can be observed in Figure 11*k*. 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.

Key Observations.

- Flying from the slope uphill and landing the drone at the slope downhill with communication between the RPICs, VO, or both, 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.

Applications of UAVs for Highway Bridge Inspections

UAV images, based on how they are captured, enable two types of bridge inspections: (1) qualitative inspection and (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 taking equipment, and (2) they may not take a long time for data collection.

For quantitative inspection, data-collection needs to be planned with 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; some cases that might benefit from such inspections are: (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

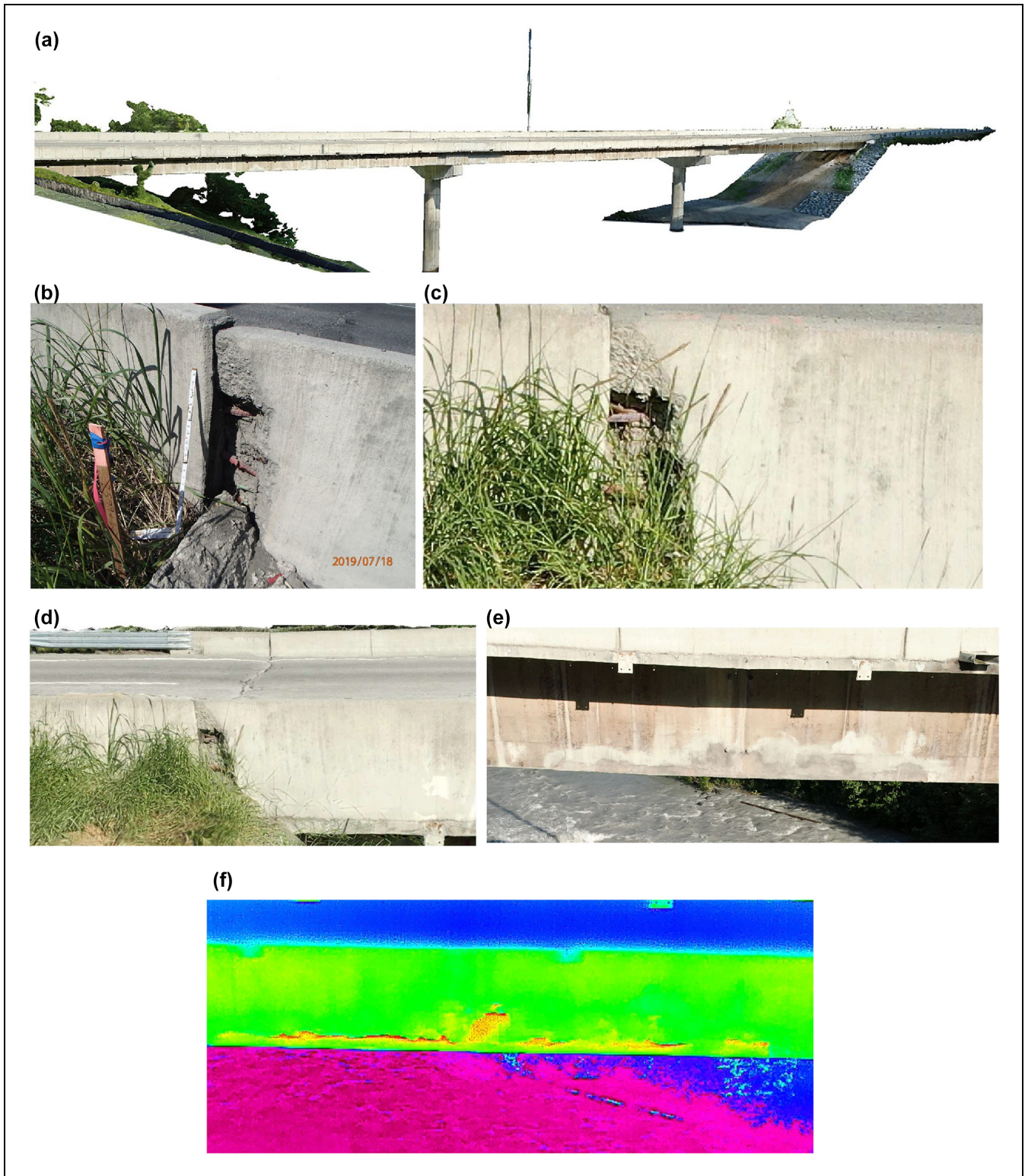


Figure 11. (continued)

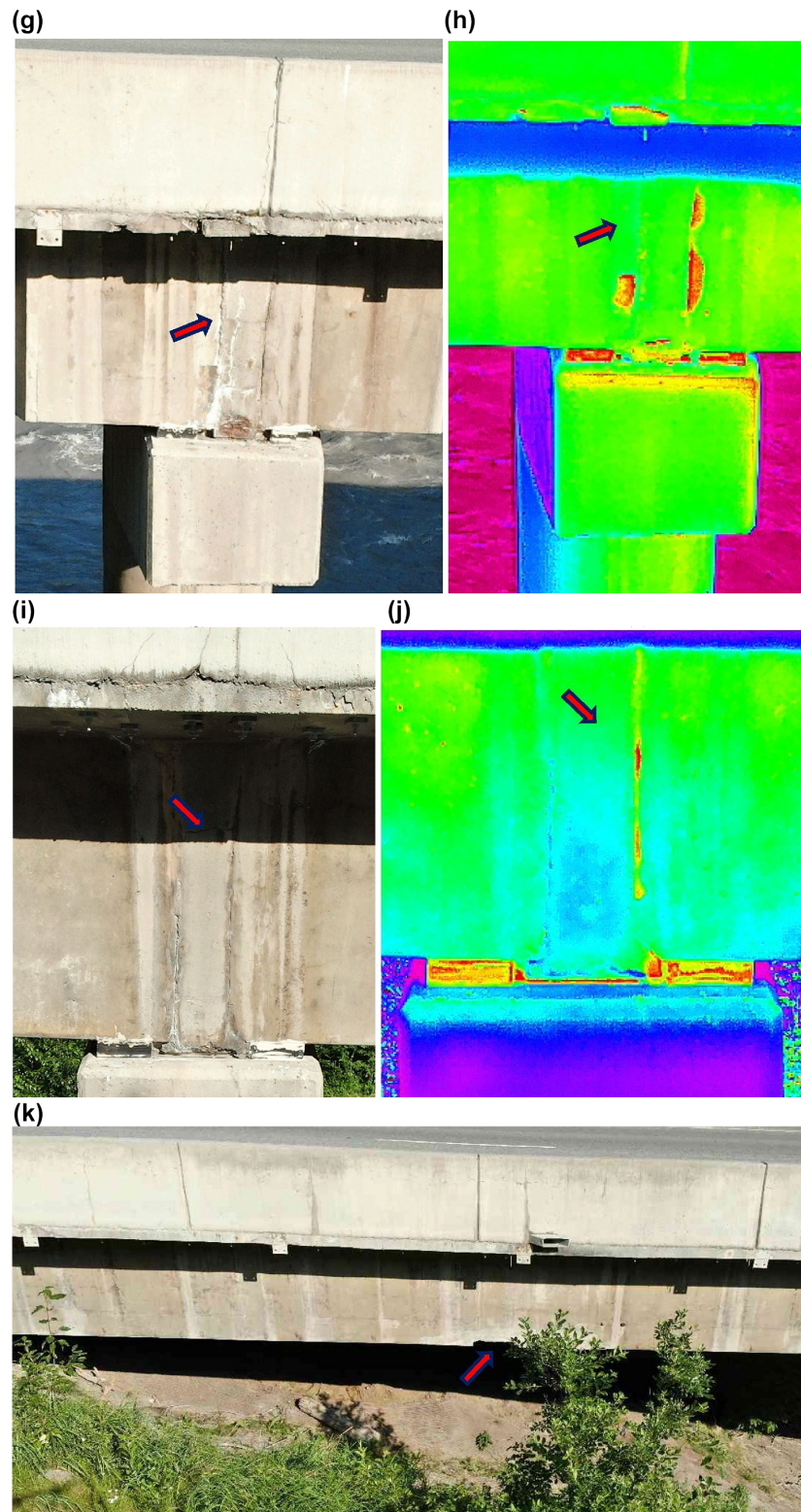


Figure 11. Eagle River Bridge condition assessments: (a) 3D model viewed from the south direction, (b) railing-end spall identified during the routine inspections in 2019, (c) rail-end spall in the aerial RGB image, (d) railing-end spall and asphalt crack in the 3D model viewed from the southeast, (e) 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, and (k) concrete falloff on south side face of the bridge.

Table 3. Potential Applications of Uncrewed Aerial Vehicles (UAVs) for Highway Bridge Inspections

S. No.	Inspection category	Application of UAVs	Remarks
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
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
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
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 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
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
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

Recommendation Scale



Note: Where 10 is highly favorable and 0 is not favorable.

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 with 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 owing to the reduced deployment time for 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 3.

Conclusions

This paper presents a methodology and 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 for DOT agencies and practitioners. The digital replicas of the bridges helped in conducting quantitative assessments. As reported by previous literature, orthorectified and stitched images being overlaid on the bridge plans were found to help provide the 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 resulting from 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 the location can be difficult to differentiate. Poor GPS conditions also contribute to this issue. Therefore, 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.

Based on the comparisons between traditional routine inspection reports and UAV-based inspections of different types of bridges inspected in this study, the potential applications of UAVs for highway bridge asset management were provided to guide the practitioners and DOT agencies.

Author Contributions

The authors confirm their contribution to this paper as follows: study conception and design: Surya S. C. Congress, Jesse Escamilla III, and Anand J. Puppala; data collection: Surya S. C. Congress, Jesse Escamilla III, Hiramani Chimaurya, and Anand J. Puppala; analysis and interpretation of results: Surya S. C. Congress, Jesse Escamilla III, and Anand J. Puppala; draft manuscript preparation: Surya S. C. Congress and Anand J. Puppala. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors would like to thank The Alaska Department of Transportation & Public Facilities (Alaska DOT&PF) and Federal Highway Administration (FHWA) for funding projects 2521H033 and 2523H032. We acknowledge Anna Bosin, Ryan Marlow, Erin Anderson, Kamron Jafari, and Shane Moller for their support toward the project tasks. We would also like to acknowledge the NSF Industry-University Cooperative Research Center (I/UCRC) program-funded “Center for Integration of Composites into Infrastructure (CICI)” site at Texas A&M University (Program Director: Dr. Prakash Balan, Division of Industrial Innovation & Partnerships; Award # 2017796) and its research team, the Center for Infrastructure Renewal (CIR), the High-Performance Research Computing (HPRC), and the Texas Virtual Data Library (ViDaL) at the Texas A&M University for their partial support. We would like to thank North Dakota State University and Skydio Inc. for their support.

ORCID iDs

Surya Sarat Chandra Congress  <https://orcid.org/0000-0001-5921-9582>

Hiramani Chimaurya  <https://orcid.org/0000-0003-2751-539X>

Anand J. Puppala  <https://orcid.org/0000-0003-0435-6285>

Data Accessibility Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author on reasonable request.

References

1. ASCE. *America's Infrastructure Report Card 2021*. American Society of Civil Engineers, 2021. <https://infrastructure-reportcard.org/>. Accessed March 6, 2021.
2. Barfuss, S. L., A. Jensen, and S. Clemens. *Evaluation and Development of Unmanned Aircraft (UAV) for UDOT Needs*. Utah Department of Transportation. Research Division, Salt Lake City, 2012. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1005&context=water_pubs. Accessed March 6, 2021.
3. Congress, S. S. C. *Novel Infrastructure Monitoring Using Multifaceted Unmanned Aerial Vehicle Systems - Close Range Photogrammetry (UAV - CRP) Data Analysis*. Doctoral dissertation. The University of Texas at Arlington, 2018. <https://rc.library.uta.edu/uta-ir/handle/10106/27746?show=full>.
4. Brooks, C., R. J. Dobson, D. M. Banach, D. Dean, T. Oommen, R. E. Wolf, T. C. Havens, T. M. Ahlborn, and B. Hart. *Evaluating the Use of Unmanned Aerial Vehicles for Transportation Purposes*. Michigan Department of Transportation. Research Division, 2015. <https://rosap.ntrl.bts.gov/view/dot/28859>.
5. Dorafshan, S., M. Maguire, N. V. Hoffer, and C. Coopmans. Challenges in Bridge Inspection Using Small Unmanned Aerial Systems: Results and Lessons Learned. *Proc., International Conference on Unmanned Aircraft Systems (ICUAS)*, Miami, FL, IEEE, New York, 2017, pp. 1722–1730.
6. Metni, N., and T. Hamel. A UAV for Bridge Inspection: Visual Servoing Control Law with Orientation Limits. *Automation in Construction*, Vol. 17, No. 1, 2007, pp. 3–10.
7. Chen, S., D. F. Laefer, E. Mangina, S. I. Zolanvari, and J. Byrne. UAV Bridge Inspection Through Evaluated 3D Reconstructions. *Journal of Bridge Engineering*, Vol. 24, No. 4, 2019, p. 5019001.
8. Nasimi, R., F. Moreu, M. Nasimi, and R. Wood. Developing Enhanced Unmanned Aerial Vehicle Sensing System for Practical Bridge Inspections Using Field Experiments. *Transportation Research Record: Journal of the Transportation Research Board*, 2022. 2676: 514–522.
9. Perez, M. A., W. C. Zech, and W. N. Donald. Using Unmanned Aerial Vehicles to Conduct Site Inspections of Erosion and Sediment Control Practices and Track Project Progression. *Transportation Research Record: Journal of the Transportation Research Board*, 2015. 2528: 38–48.
10. Congress, S. S. C., A. J. Puppala, C. Treybig, C. Gurganus, and J. Halley. Application of Unmanned Aerial Vehicles for Monitoring Airport Asset Surfaces. *Transportation Research Record: Journal of the Transportation Research Board*, 2023. 2677: 458–473.
11. Congress, S. S. C., A. J. Puppala, and C. Lundberg. Total System Error Analysis of UAV-CRP Technology for Monitoring Transportation Infrastructure Assets. *Engineering Geology*, Vol. 247, 2018, pp. 104–116. <https://doi.org/10.1016/j.enggeo.2018.11.002>.
12. Mikhail, E. M., J. S. Bethel, and J. C. McGlone. *Introduction to Modern Photogrammetry*. Wiley, New York, NY, 2001, p. 19.
13. McGlone, J. C., E. M. Mikhail, J. S. Bethel, and R. Mullen. *Manual of Photogrammetry*. American Society for Photogrammetry and Remote Sensing, Bethesda, MD, 2004.
14. Colomina, I., and P. Molina. Unmanned Aerial Systems for Photogrammetry and Remote Sensing: A Review. *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 92, 2014, pp. 79–97.
15. Siebert, S., and J. Teizer. Mobile 3D Mapping for Surveying Earthwork Projects Using an Unmanned Aerial Vehicle (UAV) System. *Automation in Construction*, Vol. 41, 2014, pp. 1–14.
16. Congress, S. S. C., and A. J. Puppala. Eye in the Sky: Condition Monitoring of Transportation Infrastructure Using Drones. *Proceedings of the Institution of Civil Engineers - Civil Engineering*, Vol. 176, 2023, pp. 40–48.
17. Congress, S. S. C., A. J. Puppala, A. Gajurel, and N. H. Jafari. Transforming Aerial Reconnaissance Data of Pavement Infrastructure into Knowledge for Better Response to Natural Disasters. In *Proc., Geo-Extreme 2021* (C. L. Meehan, M. A. Pando, B. A. Leshchinsky, and N. H. Jafari, eds.), American Society of Civil Engineers, Reston, VA, 2021, pp. 183–193.
18. Zhang, C. An UAV-Based Photogrammetric Mapping System for Road Condition Assessment. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 37, 2008, pp. 627–632.
19. Inzerillo, L., G. Di Mino, and R. Roberts. Image-Based 3D Reconstruction Using Traditional and UAV Datasets for Analysis of Road Pavement Distress. *Automation in Construction*, Vol. 96, 2018, pp. 457–469.
20. AKDOT&PF. *Alaska Bridges and Structures Manual*. Alaska Department of Transportation, 2017. <https://dot.alaska.gov/stwddes/desbridge/bridgemanual.shtml>.
21. Ryan, T. W., J. EricMann, Z. M. Chill, and B. T. Ott. *Bridge Inspector's Reference Manual*, Vol. BIRM 1. Publication No. FHWA NHI 12-049. United States, Federal Highway Administration, Arlington, VA, 2012. <https://www.dot.state.mn.us/bridge/pdf/insp/birm/birmchapt0-cover.pdf>.
22. Wells, J., and B. Lovelace. *Unmanned Aircraft System Bridge Inspection Demonstration Project Phase II Final Report*. Minnesota Department of Transportation. Research Services & Library, Minneapolis, MN, 2017.
23. Gillins, D. T., C. Parrish, M. N. Gillins, and C. Simpson. *Eyes in the Sky: Bridge Inspections with Unmanned Aerial Vehicles*. No. FHWA-OR-RD-18-11. United States, Federal Highway Administration, Salem, OR, 2018.
24. Congress, S. S. C., A. J. Puppala, M. A. Khan, N. Biswas, and P. Kumar. Application of Unmanned Aerial Technologies for Inspecting Pavement and Bridge Infrastructure Assets Conditions. *Transportation Research Record: Journal of the Transportation Research Board*, 2022. <https://doi.org/10.1177/03611981221105273>.
25. Puppala, A. J., and S. S. C. Congress. *Implementation of Unmanned Aerial Systems Using Close-Range*

- Photogrammetry Techniques (UAS-CRP) for Quantitative (Metric) and Qualitative (Inspection) Tasks Related to Roadway Assets and Infrastructures*. Texas Department of Transportation, Austin, 2021. <https://library.ctr.utexas.edu/hostedpdfs/uta/5-6944-01-ipr1.pdf>.
26. Karimoddini, A., T. L. Cavalline, S. P. Beth, H. P. Rodward, and A. Homaifar. *UAV Selection Methodology and Performance Evaluation to Support UAV-Enabled Bridge Inspection*. North Carolina Department of Transportation, Raleigh, NC, 2022. https://connect.ncdot.gov/projects/research/RNAProjDocs/2020-23_Final%20Report.pdf.
 27. Tomiczek, A. P., T. J. Whitley, J. A. Bridge, and P. G. Ifju. Bridge Inspections with Small Unmanned Aircraft Systems: Case Studies. *Journal of Bridge Engineering*, Vol. 24, No. 4, 2019, p. 5019003.
 28. Neubauer, K., E. Bullard, and R. Blunt. *Collection of Data with Unmanned Aerial Systems (UAS) for Bridge Inspection and Construction Inspection*. NO. FHWA-HRT-21-086. United States, Federal Highway Administration, Office of Infrastructure, McLean, VA, 2021.
 29. Congress, S. S. C., A. J. Puppala, P. Kumar, A. Banerjee, and U. D. Patil. Methodology for Resloping of Rock Slope Using 3D Models from UAV-CRP Technology. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 147, No. 9, 2021, p.05021005. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0002591](https://doi.org/10.1061/(ASCE)GT.1943-5606.0002591).