TECH**BRIEF**

Effective Practices for Routine Bridge Inspections Using Unmanned Aerial Systems

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This document is one in a series of technical summaries that accompany the forthcoming Federal Highway Administration report, *Collection of Data with Unmanned Aerial Systems (UAS) for Bridge Inspection and Construction Inspection*.

INTRODUCTION

A number of early adopting State departments of transportation (DOTs) are incorporating unmanned aerial systems (UAS) into routine bridge inspection processes. During the initial inspections and proof-of-concept projects, these States—Maine, Minnesota, and Utah—developed many practices that, when followed, will benefit other organizations as they develop their UAS inspection programs. The effective practices discussed in this TechBrief involve supplementing traditional inspection techniques with UAS during routine inspections, supplementing traditional bridge deck condition inspections using infrared (IR) sensors, and capturing UAS imagery of an entire bridge structure to create a three-dimensional (3D) model. These practices have been demonstrated to improve inspection safety, save inspection costs and time, and improve process efficiencies.

BACKGROUND

Traditionally, engineers and inspectors have conducted bridge inspections by using a variety of equipment and tools. These inspections can take many hours and require significant levels of funding to accomplish. The introduction of UAS into the inspection process is a means to decrease the time required for the inspection, save on inspection costs, and reduce risks to inspection teams.

Many State DOTs are integrating UAS into their bridge inspection processes: some as proof of concept projects, and others as a key tool used regularly by inspectors to supplement traditional bridge inspection procedures. Three States at the leading edge of this rapidly advancing technology are Maine, Minnesota, and Utah. This TechBrief describes techniques or processes used by these States that, at the time of publication, are considered "effective practices."

The practices discussed relate to the following applications of UAS to bridge inspections:

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- Supplementing traditional inspection techniques during routine inspections.
- Supplementing traditional bridge deck condition inspections using IR sensors.
- Using UAS to capture imagery of an entire bridge to create a 3D model.

Using UAS in these inspection applications illustrates how UAS can save time and costs, enhance safety for the inspection team and the traveling public, and provide inspection information capable of being recalled and shared in new ways.

Each of these applications is illustrated in a case study. In two cases, the studies describe a cost effective application of UAS for bridge inspections. In the third case, the use of UAS does not add significant financial value to the established processes, but it does mitigate risks to the inspection team. The case studies examine the inspection tasks and unique challenges presented by the bridges inspected and how the challenges were addressed.

EFFECTIVE PRACTICES FOR ENHANCING SAFETY AND EFFICIENCY

For bridge inspections, the most common use of UAS is to supplement traditional, routine inspection techniques by imaging bridge elements that are in difficult-to-reach areas, thus enhancing inspection safety. Several practices employed by inspectors supporting MaineDOT illustrate these functions, add efficiencies to the process, and save time in conducting the inspection.

Planning and Coordination to Enhance Safety

One key advantage of using UAS during inspections is in reducing the exposure of the inspection team to safety hazards associated with difficult terrain at the bridge site. In some cases, the property near the bridge may have restricted access and require prior coordination and planning to maximize the performance of the UAS. Such conditions and the need for prior coordination were necessary for flying UAS around the Ticonic Bridge in Winslow, ME (figure 1).

Constructed in 1936 and renovated in 1990, the Ticonic Bridge is a five-lane highway bridge connecting Wilson and Waterville, ME, along US Route 201. The bridge spans the Kennebec River, Reservoir, and Dam. It supports the passage of nearly 9,000 vehicles daily, with 5 percent of the vehicles, on average, being trucks (MaineDOT 2020).

Figure 1. Photo. UAS aerial view of the Ticonic Bridge.

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The bridge is situated over fast-moving water and a dam. Additionally, the terrain on either side of the bridge includes a combination of trees and steep bluffs above the water. These conditions make accessing the areas under the bridge, so that the pilot can keep sight of the UAS, hazardous by boat and impossible from the shore.

The inspection team planned for this challenge by coordinating with the owner of the dam to gain access to the dam structure. This access enabled the inspection team members, especially the UAS pilot, to walk out onto the dam and position themselves safely at or near the water level below the bridge. Thus, the team was able to visually navigate the UAS underneath the bridge structure. If needed, the inspection team was prepared to use a boat to serve as the UAS landing area or beach the boat downstream of the dam to maintain line of site. Both alternatives posed significant risk to the inspection team, given the velocity of the water. With access to the dam approved, these options were not needed, thus reducing safety risks to the inspection team. This level of coordination allowed the team to capture imagery of specific structural areas underneath the bridge deck that were inaccessible using an under-bridge-inspection truck (UBIT).

The bridge structure consists of steel-welded plate girders and riveted plate girders supporting a concrete cast-in-place bridge deck. On the south side of the bridge is a pedestrian sidewalk, which is part of the original rail bridge constructed as soil-filled spandrel arches (figure 2). The arches on the south side of the bridge cannot support the weight of a UBIT, and the bridge is too wide for a UBIT to reach the south side when positioned on the north side. Thus, UAS flights eliminated the safety hazards of using other means (typically an inspector climbing underneath the arches) to access the south side of the bridge deck to capture high-resolution imagery to assess the structural condition.

Figure 2. Photo. UAS image of Ticonic Bridge spandrel arches.

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Integrating UAS into the inspection process provided the inspector with key advantages, including the ability to capture images of areas under the south side of the wide bridge deck between the steel girders and the deteriorating spandrel arches. Using the UAS, the inspector could view and identify bridge structure defects, such as spalling and loose concrete, at a close range. The images captured by the UAS were high quality, allowed the inspector to accurately evaluate the condition of the bridge, and were more than suitable for inclusion in the final inspection report submitted to MaineDOT.

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

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

Two-Person UAS Team

While the use of a UAS during inspections can enhance safety and efficiency alone, the practice of employing the platform via a two-person team adds to these advantages. UAS technology and flight control systems have made the platform very easy to fly in open spaces. This result can lead to the perception that, with a little practice, flying a UAS in support of bridge inspections can be done by one person flying the platform and monitoring the imagery being captured. While in certain cases this practice can be a practical way to employ UAS, those with extensive experience in the field feel the use of UAS is fully realized when a two-person team is employed.

The dual-control inspection team setup consists of a UAS pilot and a sensor operator (typically the inspector or inspection team leader) performing their tasks using separate controllers. The UAS pilot controls the UAS position during flight, ensuring the safety of the platform and the surroundings, and getting the UAS in position to attain the desired images and video. There are two video feeds from the UAS in this setup: a "first-person view" camera for the UAS pilot, and a second high-resolution camera that can capture inspection video and still images. The sensor operator directs the onboard camera and can adjust, while the platform is in flight, the gimbal angle, zoom (if equipped with variable focal length lens), and multiple camera settings to achieve the highest quality inspection imagery possible.

Figure 3 depicts the inspection team at the Ticonic Bridge using this setup. The sensor operator (in the foreground) is the bridge inspector. Using the dual controls, the inspector can focus on capturing the needed images of the bridge structure while the pilot (in the background) concentrates on safely flying the aircraft.

The two-person team approach used at Ticonic Bridge allowed the pilot to maneuver the platform safely into positions where the inspector could see the bridge components in real time to make a visual evaluation

Figure 3. Photo. Two-person inspection team using separate monitors.

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of the structure components and identify defects for areas hazardous to access by other means (figure 4 through figure 6).

In addition to having the inspector view the live imagery on a separate monitor, the team in Maine also set up a "field office" to view the UAS imagery in between flights. At the time of this inspection, the resolution of the live video was limited by the size and quality of the monitor and the means by which the data were streamed from the air vehicle. The highest quality imagery the inspector could review was stored on the portable media on the aircraft, which can save all video and designated still images for the time the UAS is in flight, and perhaps for the entire inspection, if the media has a large enough storage capacity. The team at the Ticonic Bridge used a van with screens and curtains to black out the cab so that the inspector could view the data directly from the UAS memory card on a high-definition monitor without environmental interference. This practice allowed the inspector, while still in the field, to accurately evaluate the condition of the bridge and select the best imagery suitable for inclusion in the final inspection report that would be submitted to MaineDOT. The success of this approach led to MaineDOT determining that future inspections of the Ticonic Bridge would include a UAS.

Figure 4. Photo. Key area of interest for UAS imaging.

Original photo: © 2020 VHB. Modified by FHWA to add arrow showing area of interest.

ASSESSING BRIDGE DECKS WITH IR SENSORS

An emerging use of UAS is the employment of platforms carrying IR sensors to detect and assess concrete bridge decks for defects. These sensors detect differences in temperatures of the objects and surroundings being viewed. While this application is in the proof-of-concept and testing phase (at the time of this research), Utah DOT (UDOT) has explored this UAS mission with multiple sensors and discovered some effective practices that can enhance the results.[1]

UDOT's proof-of-concept inspections to date focus on the use of IR sensors for inspecting concrete surfaces for delamination and other defects. They have explored this use on multiple bridges in the State. A six-lane divided highway bridge on Interstate 80 in downtown Salt Lake City, UT, is used as an example for this discussion (figure 7). This bridge is on a major route through the city, and using UAS for inspection

Figure 5. Photo. UAS image of space between spandrel arches and primary bridge structure.

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Figure 6. Photo. UAS image of deterioration between steel girders and spandrel arches.

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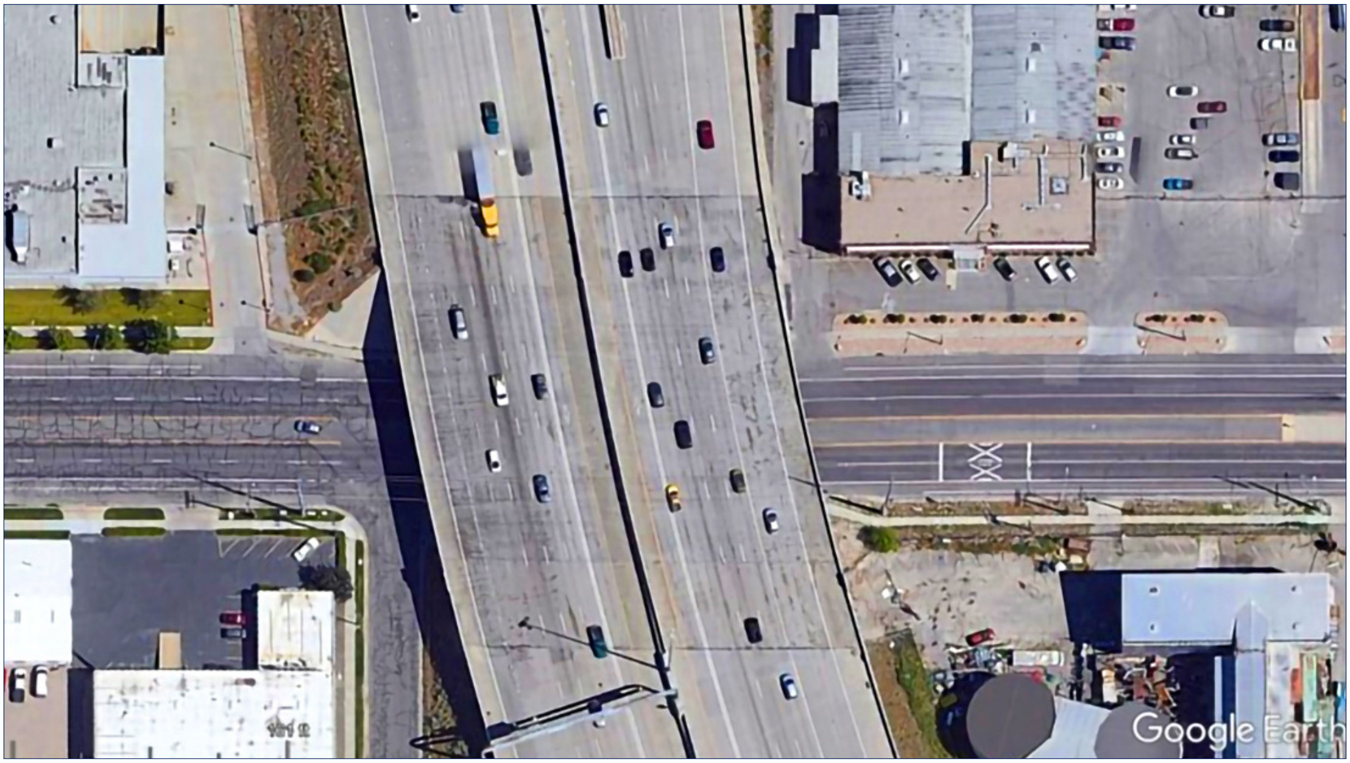
[1] Paul Wheeler, Lead UAS Coordinator and Technology Advancement Specialist, interviewed by Futron Aviation on October 2, 2019.

Figure 7. Photo. Utah proof-of-concept highway bridge in Salt Lake City, UT.



purposes benefits the inspection team and the public by minimizing the disruption of the continuous traffic that transits the bridge daily.

The IR inspection was conducted while previously scheduled work was being performed, so traffic control was already in place. Although use of the IR sensors on UAS is still in the exploration and learning phase, the imagery captured produced usable results for inspection reporting purposes. When a camera of sufficient quality is used, the inspector can identify delamination that would normally require sounding, chain dragging, or using handheld IR sensors, all of which require traffic control measures.

UDOT's use of two different IR sensors of different technological generations delivered varied results. The first camera used was integrated with the aircraft and overlaid an IR image atop the electro-optical (EO) image (figure 8). Due to the IR sensor's low resolution, the UAS failed to capture high quality imagery that was consistently useful for detecting and identifying delamination of the bridge deck.

The second system used an IR sensor with significantly higher resolution and allowed the inspector to identify areas of delamination that would not have been visible with the first camera. Using the advanced camera, the inspector in one instance was able to identify an area of delamination that had been missed using traditional inspection techniques (figure 9). This previously undiscovered delamination was verified when an inspector subsequently sounded the area.

Figure 8. Photo. EO image with IR overlay.

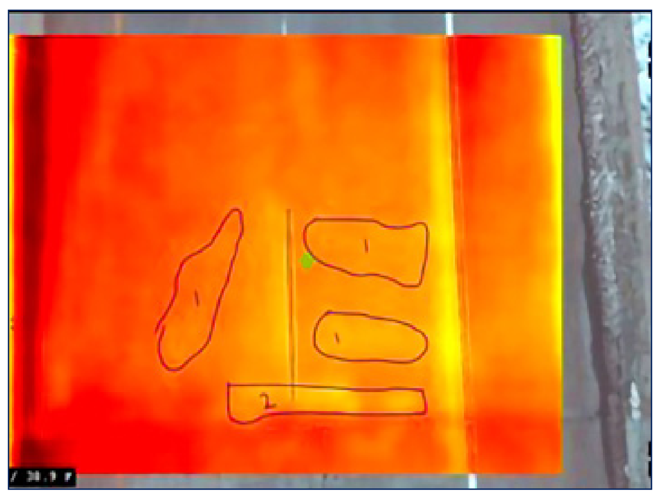
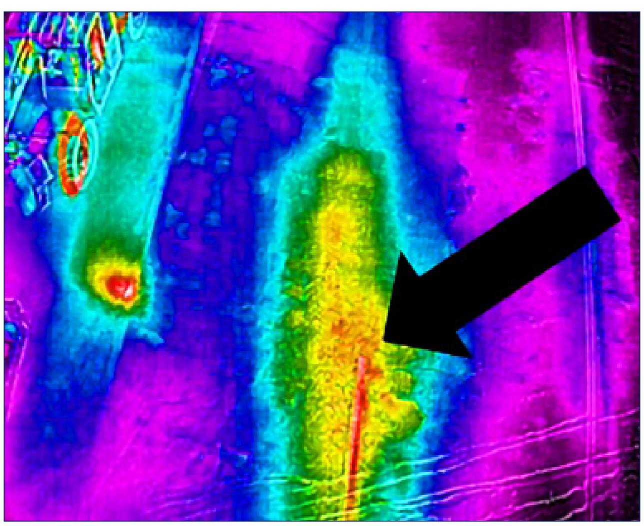


Figure 9. Photo. EO and IR sensor images showing location of previously undetected delamination.

Original photo: © 2020 Utah DOT. Modified by FHWA by adding arrows to show areas of interest.

Each of the IR sensors used had the potential to produce false positives: the first camera due to the poor resolution, and the second camera due to the higher resolution. The high resolution images could detect the thermal variations of the stringers below the concrete deck (figure 10). This action has the potential of showing as a false positive for a delamination or obscuring an actual delamination.

Figure 10. Photo. Thermal image of stringer below the bridge deck.



Original photo: © 2020 Utah DOT. Modified by FHWA by adding arrow to show area of interest.

During these inspections, UDOT discovered that the quality of the IR images was affected both by the time of day the images were captured and by the presence of equipment or debris on the bridge deck. Regardless of the quality of the system used, conducting the UAS flights at or very near dawn or dusk aids in capturing quality imagery. The higher the sun is in the sky, the more uniform the heating of the surface and the surroundings will be. The IR sensor detects differences in temperatures. The bridge structures maintain heat longer than the air does, and different densities of the materials cool or heat at different rates. Capturing the imagery close to dawn or dusk accentuates these differences and enhances the quality of the image.

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

Even though UDOT is in the early stages of using IR, their results have shown how a UAS can assist in identifying concrete delamination. However, the IR sensor will only help the inspector focus on areas where they can see delamination; sounding or other techniques will still be required to properly confirm the extent of the delamination. Regardless, future use of UAS based IR sensors has the potential to accelerate the inspection process for bridge decks and focus traditional inspection techniques, both of which reduce risk by decreasing the need for traffic control.

Going forward, UDOT's process will include creating a database of IR images that can be used as a lifecycle tool to assist in determining how the surface is deteriorating.

CREATING 3D BRIDGE MODELS

Minnesota DOT (MnDOT), during its extensive research and pilot projects, has explored the practice of flying and imaging the entire bridge to create a 3D digital model of the structure (Wells and Lovelace 2018). This practice provides the bridge owner with many advantages, including creating a structural map of the bridge in the absence of original drawings; supplementing numeric condition data with a visual representation of the condition of the entire structure, which is useful for reviewing the data accuracy; providing location specificity for defects; comparing condition changes across inspections and assessing repair needs; and electronically archiving and recalling images of specific bridge elements and defects in an easy and sharable way (figure 11).

To capture imagery of the bridge in a repeatable manner, the inspection team can create a flight plan for the UAS that can be saved and executed multiple times and flown by many available systems. UAS navigation software can be used to create and archive these flight plans, which also include programing UAS airspeed that should not be exceeded, to ensure image clarity.

Creating a 3D model using UAS imagery does not work well for all bridge structures. One such bridge structure was discovered during a proof-of-concept inspection in Colorado. The Glenwood Springs Bridge in Garfield County, CO, is a small road bridge located on Route 134, approximately 5.5 mi to the west of Glenwood Springs, CO. It spans the Colorado River, connecting the north and south banks with Interstate 70. It has a footpath on the northern side, a rail line on the southern side, and a footbridge on the eastern side. Figure 12 shows the geography of the surrounding area.

The bridge is a concrete-deck, three-span, steel-girder bridge, approximately 248 ft long, supported by two piers. The proof-of-concept inspection was conducted to examine the feasibility of using photogrammetric techniques to create a 3D mesh to supplement numeric condition data with a visual representation of the condition of the entire structure.

Figure 11. Graphic. MnDOT 3D model of stone bridge.

Figure 12. Photo. UAS image of the Glenwood Springs Bridge and surrounding terrain.

For this bridge, the UAS cameras failed to provide adequate results for creating 3D models for several reasons. It was determined that images of structures with intricate features (beams, braces, bolts, plates, and so on) and many faces are more difficult to stitch together than structures that have more basic geometry, such as a concrete bridge (figure 13). Adding to the challenge was a lack of surface features on the relatively new steel. Concrete has more variations in surface texture, which aids in the stitching process. Because of these factors and inadequate geotagging data quality, the 3D model was not usable, leaving just the video and still images for use in creating inspection products.

Figure 13. Photo. Glenwood Springs Bridge structural members being imaged by a UAS.

© 2020 ARE Corp.

The UAS images captured for the Glenwood Springs inspection fell short of the intended goal of creating a 3D model of the bridge that would be used for testing their viability for visually representing conditions across the structure. This outcome was, in large part, a result of poor geotagging due to an inadequate GPS signal. The bridge is in a ravine that limited the acquisition of GPS signals, making UAS navigation and image geotagging challenging.

BENEFITS OF THE EFFECTIVE PRACTICES

UAS in general can bring efficiencies to the bridge inspection process, including safety—both for the inspector and the traveling public; cost—by reducing or eliminating the requirement for traditional access methods such as the UBIT; time requirements—by obtaining real-time images of the structure, thus allowing the inspector to make a determination of whether a member needs physical inspection without having to rely on traditional access methods; and personnel efficiencies—by reducing or eliminating the need for traffic control and equipment operators.

Safety

During the inspections cited, several safety improvements were identified, including reducing the inspectors' exposure to traffic hazards, minimizing the need to traverse streams or riverbeds, reducing or eliminating the need for traditional access methods (such as climbing) that put the inspector at risk and the extra gear the methods require, and reducing or eliminating traffic control measures that would impact the traveling public.

Cost

The cost to perform a routine inspection will vary from bridge to bridge, adding up to many thousands of dollars for traffic control, equipment rental, and labor hours for the inspection team. As demonstrated in these examples, following these effective practices may reduce or eliminate the need for expensive equipment (such as UBIT) and reduce the time required for the inspection, thus saving labor hours for the inspection team and for traffic control personnel. Some examples of the savings associated with the practices are as follows:

- Ticonic Bridge—The UAS team and equipment were contracted as a package for a daily rate. This rate included all labor for the UAS pilot and the cost of the UAS equipment. As a result of using the UAS team, the Ticonic Bridge inspection was conducted in just 1 d, compared with at least 2 d in past inspections, thus reducing the costs for UBIT use and traffic control.
- Utah bridges—Because the inspections in Utah using UAS with IR sensors are in the proof-of-concept phase, their cost savings have not been accurately determined; however, UDOT did note that using the UAS to conduct inspections of overhead traffic signs was saving the State a great deal of time and money. Using UAS for this type of infrastructure inspection resulted in the ability to inspect 16 signs in 1 d without using traffic control, as opposed to 3 to 4 signs in 1 d using conventional methods. This application using a UAS resulted in approximately $100K in savings, $80K of which was in traffic control alone.

ADVANCED-USE SHORTFALLS—PROCESSING TIME

A key advantage of using UAS during inspections is the time saved in accessing parts of the bridge and having real-time video of the structure for the inspector to view. That said, the time saved in the field performing inspections can, in certain cases, be reduced by the additional time needed to process the data captured by a UAS, particularly if a 3D model is created using the imagery. The method of creating 3D graphics from two-dimensional images is called structure from motion (SfM). This method uses multiple overlapping images to create products like 3D models and orthophotos using photogrammetry software applications. MnDOT has done extensive work using UAS for 3D modeling of bridges and has shown that the cost and time savings gained are worthwhile. However, creating SfM reduces the level of efficiency gained using UAS. The total time required to conduct a traditional inspection for the bridge depicted in figure 11 was 11 h, whereas the inspection using a UAS took over 9 h of flight time, and the postprocessing of the imagery increased the overall time invested in this bridge to over 17 h (Wells and Lovelace 2018).

The time required for the Glenwood Springs Bridge data postprocessing was approximately 32 h. No cost was included for the postprocessing, but this number of hours is considerable for a single bridge. This amount of time needed to create a 3D model would not be necessary for most routine inspections.

LESSONS LEARNED AROUND THE EFFECTIVE PRACTICES

Throughout the course of each of these bridge inspections using UAS, many lessons were learned about how UAS can best be applied during bridge inspections, as follows:

- UAS improves on the means to access areas that are difficult or hazardous to reach due to physical restrictions, like challenging terrain, bridge dimensions, or weight restrictions.
- Inspection results can be enhanced by determining beforehand where the UAS can best be used to supplement the inspection and developing a flight plan to gain access to all areas around the bridge.
- The ability to review the imagery between flights improves inspection results. Performing a final review of all defect imagery captured before leaving the site improves inspection results and efficiency.
- The right IR sensor and the proper training in its use enhance the ability of the user to interpret the IR images and reduces the number of false positives.
- UAS may not be optimal for all steel structures with intricate or enclosed architecture.
- It is difficult to extract images usable for 3D modeling from bridges without many surface features.

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