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Field Application of UAS-Based Bridge Inspection

Junwon Seo[1], Luis Duque[1], and James P. Wacker[2]

Abstract

The use of Unmanned Aerial Systems (UASs), commonly known as drones, has significantly increased over recent years in the field of civil engineering. In detail, the need for a more efficient alternative for bridge inspection has risen because of the increased interest from bridge owners. The primary goal of this paper is to evaluate the efficiency of a drone as a supplemental bridge inspection tool. To complete this study, a glued laminated (glulam) girder with a composite concrete deck bridge was chosen in South Dakota, and a Dà-Jiāng Innovations (DJI) Phantom 4 drone, was employed to perform the bridge inspection. Based on the literature review, an inspection procedure with a drone was developed to efficiently identify damage on the bridge. A drone-enabled inspection was performed following the procedure, and resulting images were checked with those available in the past inspection report from South Dakota Department of Transportation (DOT). This study includes UAS-based bridge inspection considerations to capture appropriate image data necessary for bridge damage determination. A key finding demonstrated throughout this project is that different types of structural damage on the bridge were identified using the UAS.

Unmanned Aircraft Systems (UASs), referred to as drones, have assisted in visual inspection of different types of structures such as bridges in recent years (*1*). The use of UASs has become more appealing to bridge owners, researchers, and stakeholders because of their efficiency and effectiveness to gather relevant data in shorter time and at a lower cost compared with traditional inspection methods (*2*). Recent research efforts have been made to not only investigate but also to monitor structures. For instance, Chen et al. (*3*) developed a small-format aerial photography (SFAP) methodology to monitor cracks on the deck surface. To accomplish this, geo-referenced pictures were taken at an altitude of 305 m (1,000 Ft) to visually observe the damage. Chen et al. concluded that SFAP is a promising tool for bridge construction monitoring. Another investigation of the UASs' capabilities by Chen and Hutchinson (*4*) was conducted to monitor bridges. Their main goal was to monitor cracks' propagation through an image-based approach. The methodology used included images taken at different periods of time to observe the crack location, propagation, and geometric quantification. Due to its effectiveness, this emerging technology presents great potential for bridge inspection, as these structures often present inaccessible areas for inspectors (*5*).

Currently, approximately 9.1% of the United States' bridges are classified as structurally deficient (*6*). Despite the quantity of deficient bridges declining in recent years, visual inspection of such bridges needs to be conducted to effectively recognize damage and determine the appropriate retrofit methods. Several state departments of transportation (DOTs) have investigated UASs as a bridge inspection tool. For example, Caltrans developed a twin-motor, single-duct, electric-powered UAS designed to carry cameras for visual inspection of bridges (*7*). Similarly, Florida DOT and Otero used a multi-rotor helicopter-based UAS with high-definition cameras to transmit video data of structural components of bridges, including timber bridges (*8*). Some stress cracks on bearing areas and guardrail supports were detected by investigating the high-resolution images captured from the UAS. Recently, Minnesota DOT, in partnership with Lovelance and Zink, performed a research project with regard to visual inspection using UAS technology on four different types of bridges in its state (*9*). A rotor aircraft UAS with fixed wings was used for the bridge inspections. The research demonstrated the capability and advantages of the UAS, enabling damage identification on critical areas in the selected bridges in a more cost-effective and safe manner. The United States Department of Agriculture—Forest Service (USDA-FS) —Region 10 (Alaska) also developed a drone system, and its associated inspection protocols were applied to the Placer River Trail Bridge located in the Alaskan Kenai Peninsula (*5*). It was found that the drone was able to

[1]Department of Civil and Environmental Engineering, South Dakota State University, Brookings, SD
[2]Forest Service, US Forest Products Lab, Madison, WI

Corresponding Author:
Address correspondence to Junwon Seo: junwon.seo@sdstate.edu

efficiently inspect the bridge using its high-resolution scans and 3-D virtual model.

The main objective of this study was to investigate the abilities of UASs for bridge inspection. To effectively identify structural damage, a bridge inspection approach was identified and applied to an in-service bridge located in South Dakota following state and government regulations (e.g., South Dakota DOT and FAA). This paper is structured in five sections exclusive of this introduction section. The second section details the UAS and includes a bridge description to perform this application. The third section presents the bridge inspection approach based on the findings from the literature review and various guidelines from South Dakota DOT and FAA. The fourth section presents the obtained results from the damage identification and its comparison with historical inspection reports from South Dakota DOT. The fifth section presents conclusions based on findings from this work, whereas the final section details challenges raised by this UAS application to the bridge.

UAS and Bridge Choice

For this study, an appropriate UAS necessary for bridge inspections was initially selected considering different factors, including flight time, upward viewing camera, camera resolution, video resolution, and others. Then, a bridge structure was chosen to evaluate the efficiency of the UAS-based inspection. The bridge selected is a glulam, three-span timber girder bridge located near Keystone, South Dakota. The details of the UAS and structure selection are presented below.

Considered UASs

A suitable UAS needed to be chosen for the visual inspection of the bridge. While performing the literature review on UAS technology, several researchers investigated various drones to compare their capabilities with reference to data acquisition. Based on the knowledge from the literature review, the following considerations were checked to select the most suitable inspection UAS for this study:

1. **Flying time over 20 min**: A relatively long flying time is beneficial for a more efficient structure inspection, limiting the need of additional batteries and allowing for longer inspection times;
2. **Additional camera on top of UAS**: A second camera facing straight up to inspect underneath the bridge will allow for a comprehensive inspection;
3. **Camera resolution with low illumination**: Low illumination reduces the image quality and slight damage would be difficult to detect. Additional flashlights can be attached to a UAS to enhance illumination;
4. **Video resolution**: High-resolution video is required to observe details of damage;
5. **Payload capacity**: It would be beneficial for attachments that might be required to be carried by a UAS;
6. **UAS lights**: Light-emitting diode lights attached to a UAS will provide some extra illumination, which is required for efficient damage observation underneath a bridge;
7. **Remote range**: As some bridge structures might not be relatively close to the pilot location, long-range modules for remote control will allow inspection of the structure at long distances;
8. **Ability to fly without global positioning system (GPS) signal**: The ability to fly without a GPS signal allows the UAS to inspect the underside of the deck more efficiently without accidents caused by GPS signal failure.

Based on the above considerations, four UASs were deemed suitable. The appropriate UASs for structure inspection include a DJI Matrice 100, DJI S900, DJI Phantom 3 pro, and DJI Phantom 4. Other UASs studied include the Voyager 3, Yuneec Typhoon H, Yuneec Typhoon 4K, Blade Chroma, and Autel Robotics X-Star Premium. The DJI Phantom 4 was selected over the others because its performance and versatility met the aforementioned specifications at a reasonable cost. Additional equipment, such as obstacle avoidance (OA) technology, will be beneficial while approaching a bridge to prevent damage to both bridge and UAS components (*10*). Another key consideration is the ability to fly without a GPS signal. This enables the UAS to inspect underneath the bridge without the problem of losing the satellite connection. A list of specifications for the DJI Phantom 4 is presented in Table 1. Detailed information related to the UAS selection for the bridge inspection can be found elsewhere (*11*).

Studied Bridge

For the bridge inspection using the UAS, a glulam girder with a composite concrete deck bridge was selected. The bridge is presented in Figure 1. It is located on US16 to US16A highway, near the city of Keystone in Pennington County, South Dakota. The timber girder bridge has three simply supported spans with four girders spaced at 2.3 m (7.5 Ft) on center and a clear width of 7.9 m (26 Ft). The bridge is curved horizontally at an estimated radius of 116.4 m (881.97 Ft) and is 51.8 m (170 Ft) long with steel guardrails along the edges of the superstructure.

Considerations for UAS-Based Bridge Inspection

For the field bridge inspection using the UAS, there are several factors to consider before and during an inspection to ensure the collected data are gathered and analyzed correctly. For instance, both the FAA and South Dakota DOT

Table 1. DJI Phantom 4 UAS Specifications (*12*)

DJI Phantom 4 specifications	
Aircraft	
Weight (including battery)	1,380 G
Max. flight time	Approximately 28 min
Satellite systems	GPS/GLONASS
Camera	
Sensor	1/2.3" Effective pixels: 12 M
ISO range	100–3,200 (video) and 100–1,600 (photo)
Electronic shutter speed	8 s to 1/8,000 s
Max. image size	4,000 × 3,000
Max. video bitrate	60 Mbps
Photo	JPEG, DNG (RAW)
Video	MP4/MOV (MPEG—4 AVC/H.264)
Supported secure digital cards	Micro SD, max capacity: 64 GB. Class 10 or UHS-1 rating required
Gimbal	
Controllable range	Pitch: –90° to +30°
Remote controller	
Operating frequency	2.400 GHz to 2.483 GHz
Max. transmission distance	FCC compliant: 3.1 mi (5 km)
Battery	6,000 mAh LiPo 2S
Intelligent flight battery	
Capacity	5,350 mAh
Voltage	15.2 V
Battery type	LiPo 4S
Net weight	462 G
Max. charging power	100 W

Note: Max. = maximum.

Figure 1. Overview of the selected timber girder bridge captured with the UAS (captured by Luis Duque).

have limitations for the use of UASs, including no flying over 122 m (400 Ft) and no flying over traffic, respectively. A detailed description of the inspection procedure is presented as follows.

Before Inspection

To complete a bridge inspection using the UAS, it is important to consider different factors before flying the UAS. Before arriving at the bridge site, documents including construction plans and inspection reports should be reviewed to ensure efficient data collection. The construction plans review allows a pilot to recognize general information of the bridge, including structural elements locations and dimension, enhancing inspection capabilities of the UAS. For example, identifying structural elements (e.g., girders) with difficult accessibility allows an inspector to develop an approaching strategy to safely inspect the bridge using the UAS. Moreover, the review of historical inspection reports permits the location of critical damage for either monitoring or updating the damage on the bridge using the UAS.

After the bridge documentation is reviewed, the surrounding areas of the bridge must be observed to identify potential risks to flight safety (e.g., adjacent trees and traffic volume). Conducting a visual observation is necessary to identify any critical landing/takeoff zones for approaching the bridge safely. Additionally, the bridge should be visually inspected from the ground to identify critical damage areas to be inspected using the UAS. It is also required that any restrictions that may apply to the bridge location are considered. These restrictions include, but are not limited to, FAA certifications, FAA airspace class restriction [e.g., flying within 8.05 km (5 miles) of an airport], DOT flying restrictions, and DOT safety measures. Traffic controls must also be prepared for the inspection on the right-of-way of any highway per DOT regulations by displaying warning signs and cones to guide approaching traffic, to avoid work zones.

The final step before conducting the bridge inspection using a UAS is to perform a preflight check of the UAS platform to ensure the equipment is working correctly. Both the FAA and UAS manufacturers recommend a preflight check for the first flight of the day to ensure satisfactory flying performance. This check list includes, but is not limited to, propellers and rotors inspection, full charging of all instruments (e.g., a remote controller, storage batteries, and a monitor), remote controller adjustments, gimbal inspection, and firmware updates. During the bridge inspection, the UAS may lose GPS signal, especially while flying under the deck; thus, it is necessary to calibrate the compass to avoid an unanticipated signal failure and possible flyaway.

During Inspection

After the bridge documentation, visual observation, and UAS preflight check are conducted, the inspection of the bridge using the UAS can be completed. The flight strategy must consider weather limitations, FAA and DOT regulations, and others as applicable (e.g., company or organization specific limitations). For instance, it is recommended to fly the UAS during calm wind conditions [e.g., wind speeds less than 24.1 km/h (15 mph)] to avoid turbulence and complications when approaching the bridge. The data collection should be completed by gathering an overall view first before proceeding to specific structural components to ensure the capture of all damage. Limitations from DOT, including not flying over traffic, may affect data collection of the deck and other sections over any adjacent roadway due to not being able to approach them closely. It can be noted that the pilot-in-command (PIC), who must pass an initial aeronautical knowledge test at an FAA-approved knowledge testing center, can be continuously assisted by an observer as recommended by the FAA. The observer can either assist the PIC when flying close to structural components or by observing the UAS camera; therefore, the PIC avoids distractions while inspecting the bridge using the UAS.

UAS-Based Bridge Inspection

This section presents the inspection conducted on the selected bridge in accordance with the proposed procedure.

Before Inspection

The detailed review of the as-built bridge plan and corresponding past inspection report provided by South Dakota DOT was conducted. During the review, it was found that the joints of the bridge were the most critical structural component as water leakage coming from the deck had caused concrete to spall off and corrosion on the exposed rebar. For ease of damage identification, each bridge component was marked, as seen in Figure 2, for the bridge schematics. Details for the component marks on the plan and elevation views can be seen in Figure 2, *a* and *b*, respectively. A brief description of the bridge based on the construction plan is shown below.

Timber Girder Bridge

- 51.8 m (170 Ft) long;
- Glulam timber;
- Three spans, simple supported girders;
- Two bents with four columns each; and
- Curved concrete deck.

A visual observation of the bridge surroundings was conducted to identify potential risks to the operation of the UAS. The bridge was not located in a high-risk zone as there were not many large trees or structures that may have caused difficulty in approaching the bridge or may have affected the flight safety. As such, two regions adjacent to the bridge were identified as potential landing zones for approaching specific components. The UAS-based inspection of the bridge over the roadway was conducted from the edge of the roadway by the landing zones; thus, the traffic was not halted during the inspection.

Further regulations, including South Dakota DOT and FAA flying limitations, needed to be considered before conducting the inspection. For instance, South Dakota DOT specified that the UAS operation was not permitted over traffic, and liability insurance had to be obtained to protect the UAS and bridge in case of an unexpected accident. To fulfill these requirements, warning signs were placed at 228.6 m (750 Ft) from the bridges and cones near inspection zones to warn approaching traffic as requested by the South Dakota DOT. Apart from South Dakota DOT regulations, there were no other limitations for this specific bridge location. Note that the FAA regulations (i.e., Part 107 FAA Rules), to operate the UAS regardless of the use, still apply. Details of the restrictions are presented as follows:

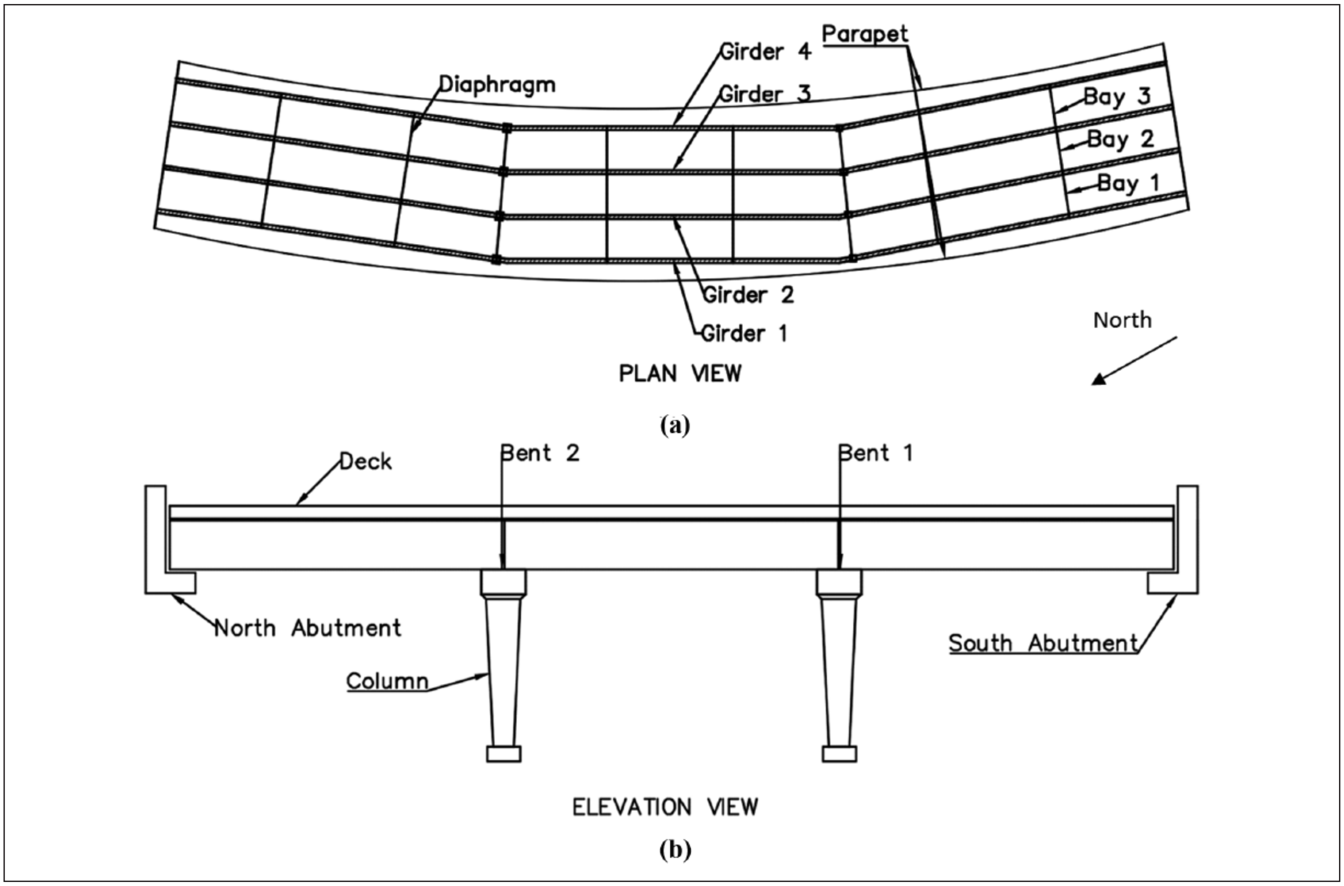

Figure 2. Bridge overview and component marks: (*a*) component marking on plan view and (*b*) component marking on elevation view.

- No restriction for Class G airspace; need air traffic control tower permission otherwise;
- Must keep the aircraft in sight (visual line-of-sight);
- Must fly under 122 m (400 Ft);
- Must fly during the day;
- Must fly at or below 100 mph;
- Must yield right-of-way to manned aircraft;
- Must not fly over people; and
- Must not fly from a moving vehicle.

The final step before the inspection of the bridge using a UAS was to conduct a preflight check. The inspection of the DJI Phantom 4 was conducted according to the manufacturer and FAA requirements. For example, rotors, propellers, batteries, iPad, remote controller, gimbal, and software updates were checked to ensure high flight operation performance. The equipment was found to be in excellent condition, and no defects that may have caused unsafe flying conditions were observed. Additionally, the compass of the UAS was successfully calibrated to avoid any signal loss or potential flyaway. To complete the calibration, the UAS was rotated counterclockwise, while being held horizontally. Then, this same process was vertically performed once more with the camera facing down. The UAS setup was completed without any issues that could have a negative influence on the flight and inspection performance.

During Inspection

After the reviews of information and precautionary actions are taken, the UAS-enabled bridge inspection can take place. The inspection using DJI Phantom 4 was completed over the course of 2 days, February 16 and 17, 2017. During the first inspection day, February 16, the weather conditions were favorable. A sample image captured using the UAS can be seen in Figure 3. To complete the inspection, the overall view of the structural elements was gathered and then specific damage was observed. During this flight, the PIC was continuously assisted by an observer to ensure the flight was safely conducted. Figure 3 shows the UAS aviation near structural components for the bridge.

The weather conditions during the second day of inspection, February 17, were not favorable because of high wind speeds of 24.1 km/h. (15 mph) and wind gusts of 43.5 km/h. (27 mph). A limited number of pictures was obtained during this day using the UAS. For this inspection, a different inspection approach was explored by using video-based

Figure 3. Sample image obtained from the timber girder bridge inspection on February 16, 2017: UAS flying near column of timber girder bridge (captured by Junwon Seo).

data acquisition to eliminate any unnecessary distractions from the picture-taking process while flying under such harsh weather conditions. Using the recorded videos, sample images were obtained to identify damage as seen in Figure 4*a*. Figure 4*a* shows concrete cracks and high moisture resulting from water leakage at the North Abutment of the bridge. It has been proved that the video-based inspection facilitated the acquisition of image information necessary for the damage identification. Figure 4*b* shows the UAS approaching components of the bridge.

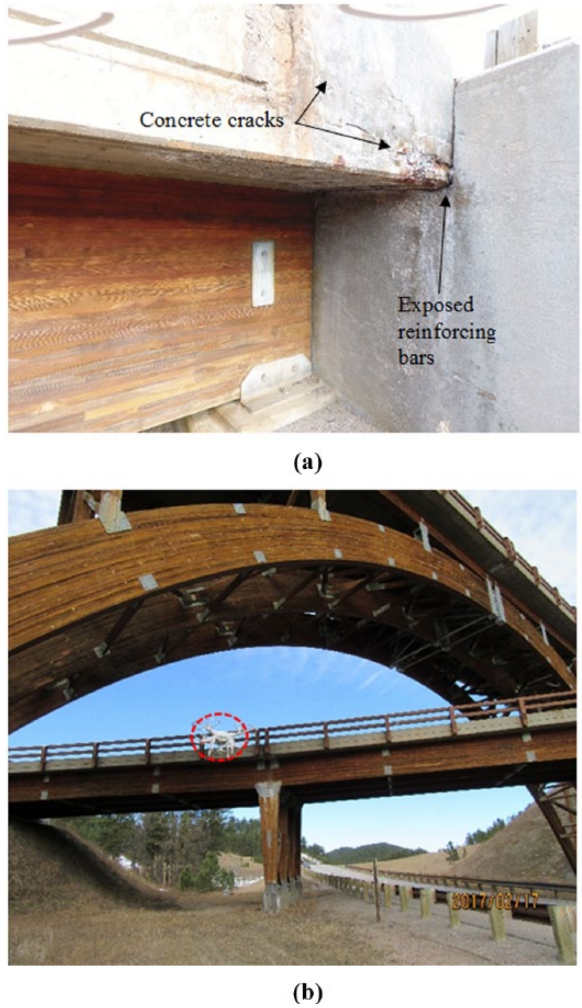

Figure 4. Sample images obtained from the timber girder bridge inspection on February 17, 2017: (*a*) concrete cracking and water damage at abutment location and (*b*) UAS approaching the bridge (captured by Junwon Seo).

Results and Discussion

This section includes the damage identified using the UAS and its comparison with images provided by South Dakota DOT. The first subsection includes a detailed damage identification for two structural elements, underside of deck and girder, whereas the second subsection provides a comparison to South Dakota DOT damage identification. Comprehensive results of the bridge inspection for the columns and abutments as well as other components can be found in Duque et al. (*11*).

UAS-Image-Based Damage Identification

The damage identification presented below aims to demonstrate the capabilities of the UAS to observe different types of damage including cracks, corrosion, and spalling. Sample results for the underside of deck and girder damage are presented as follows.

Underside of Deck. Overall, the deck had several water leakage areas causing moisture-related damage such as corrosion. Sample images of the damage are presented in Figure 5. Figure 5*a* corresponds to corrosion, spalling and exposed rebar at Girder 4 and Joint 1, and Figure 5*b* shows efflorescence in Bay 2 between South Abutment and Joint 1.

Girders. The girders were generally in good condition, with some moisture caused by water leakage resulting from the deck. Some stains and discoloration were also apparent on some girders, possibly caused by calcium deposits and corrosion coming from the chemical reaction of the water with concrete and steel. Sample images of the damage identified on the

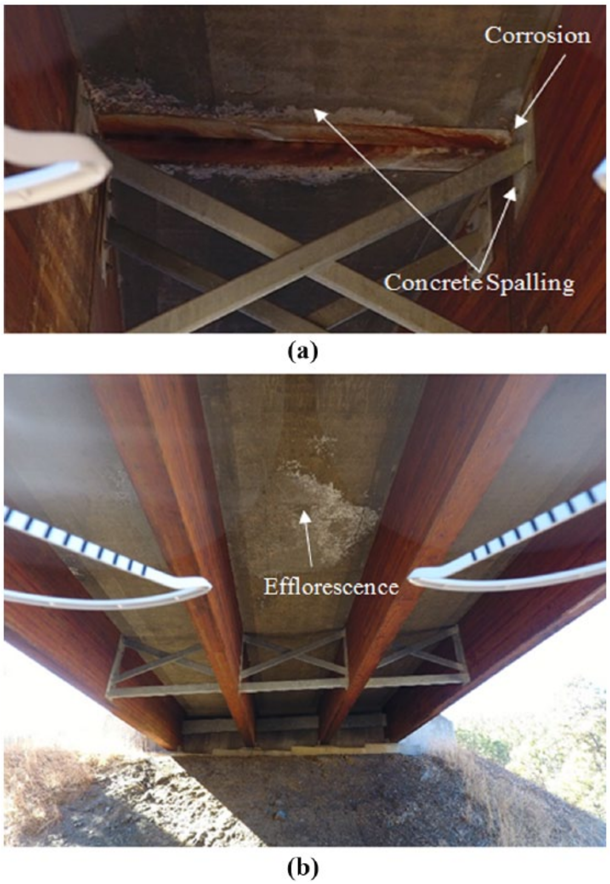

Figure 5. Underside of deck damage detected using UAS: (*a*) concrete spalling and corrosion with exposed rebar at Girder 4 and 1 and (*b*) efflorescence in Bay 2 between South Abutment and Joint 1.

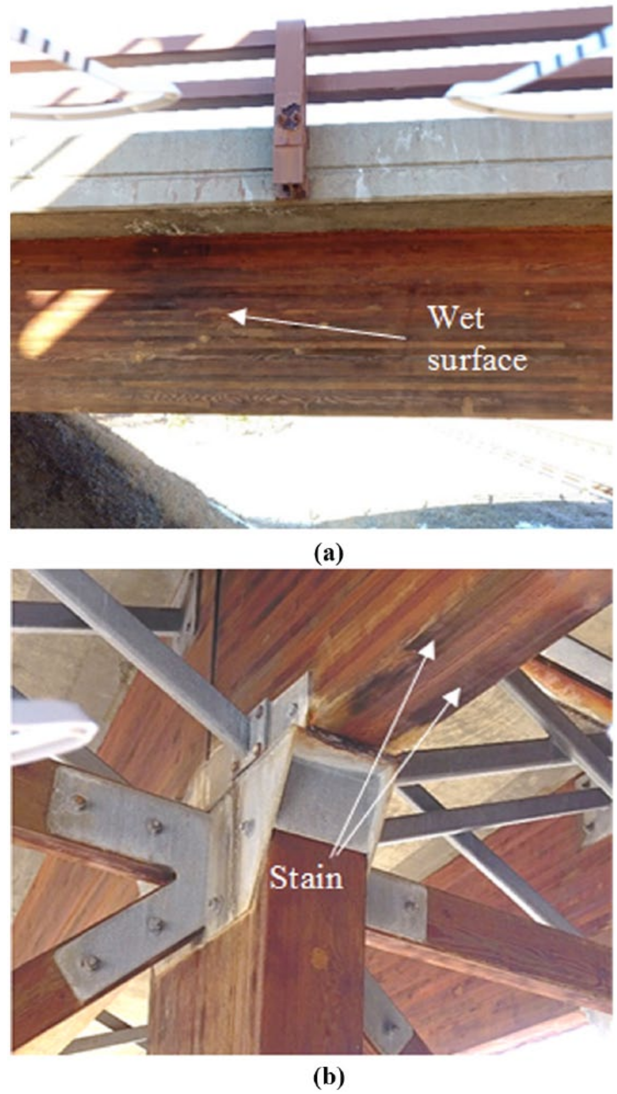

Figure 6. Girder damage detected using the UAS: (*a*) moisture damage on the side of Girder 4 between South Abutment and Joint 1 and (*b*) stains under Girder 3 at Joint 1.

girders are shown in Figure 6, *a* and *b*. Figure 6*a* shows visible moisture corresponding to Girder 4 between South Abutment and Joint 1, and Figure 6*b* shows stains under Girder 3 at Joint 1 caused by corrosion of the steel connection bracket.

Other elements. The inspection of other structural components, including abutments and pier columns, was also conducted. In detail, these elements were found to be in good condition aside from minor damage such as cracking and discoloration. For example, damage such as minor discoloration, spalling, and moisture caused by water coming from the deck at North Abutment near Girder 4 was observed, whereas some efflorescence on some column pedestals at Bent 2 was observed.

Comparison to Images from Traditional Inspection

After completing the UAS-enabled inspection, a comparison of results for the underside of the deck and girder was conducted to demonstrate the effectiveness of data obtained with the UAS. A sample image provided by South Dakota DOT is included for each structural component to visually compare the results obtained.

Deck. The UAS was able to identify the damage underneath the deck as identified from the South Dakota DOT inspection report. As reported before, some concrete spalling, delamination, and cracking were observed near joints and abutments. Figure 7 shows sample damage on the deck captured using the UAS. A representative picture provided by the South Dakota DOT (see Figure 7*a*) is included to visually compare the quality of images between the South Dakota DOT and the UAS-enabled bridge inspection. The partial

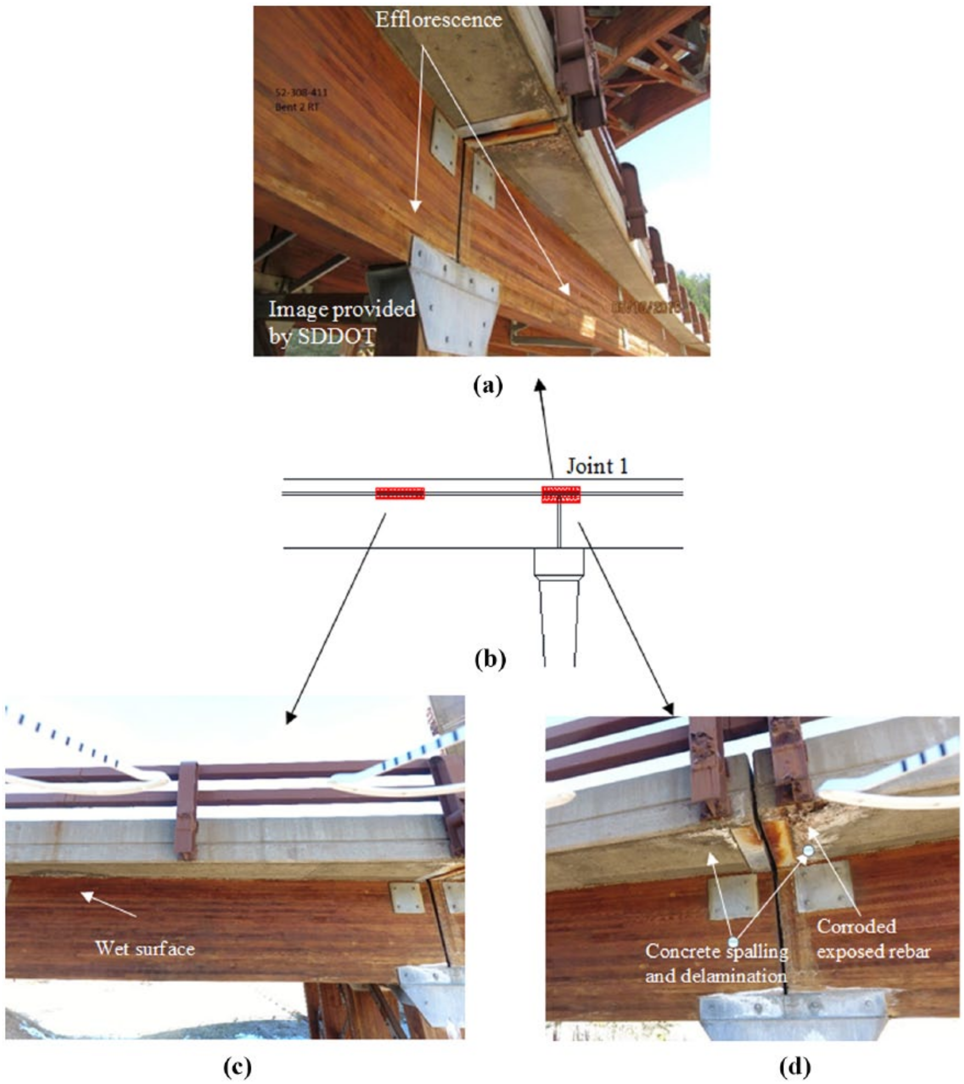

Figure 7. Sample damage on deck near Girder 4: (*a*) image provided by South Dakota DOT (*13*), (*b*) damage locations, (*c*) water leakage under deck between South Abutment and Joint 1, and (*d*) concrete spalling and corrosion with exposed rebar near Girder 4 at Joint 1.

bridge plan containing the specific damage locations represented by red hatched boxes is included in Figure 7*b*. It is apparent that the images are comparable, and the damage is identified. The water leakage under the deck between South Abutment and Joint 1 (see Figure 7*c*) and cracking, spalling, and exposed rebar (see Figure 7*d*) were identified using the UAS. Only one quantified area of damage was provided by the South Dakota DOT. The damage is identified as a 0.3 m (1 Ft) by 0.6 m (2 Ft) spalled area with exposed rebar at Joint 1. The same area was calculated using an image-based methodology detailed in Duque et al. (*11*). The results for the measurement was 0.18 m^2 (1.96 Ft^2). It can be observed that the results are identical, confirming the ability of the UAS to identify and quantify damage on the structure.

Girders. The damage detected on the girders using the UAS coincided with the report provided by South Dakota DOT. A picture provided by South Dakota DOT (see Figure 8*a*) is included to compare with those taken by the UAS. Several damaged areas caused by high moisture content were localized on the girders (see Figure 8*b*). For example, some moisture on Girder 4 between South Abutment and Joint 1 was identified, as seen in Figure 8*c*. Girders damaged because of high moisture were also recognized in other areas, especially near joints, as seen in Figure 8*d*. Note that the South Dakota DOT does not specify moisture-related damage of Girder 4 between South Abutment and Joint 1 and Girder 4 between North Abutment and Joint 2. Finally, the South Dakota DOT did not report quantifiable damage apart from a 5.08-cm (2-in.) by 5.08-cm

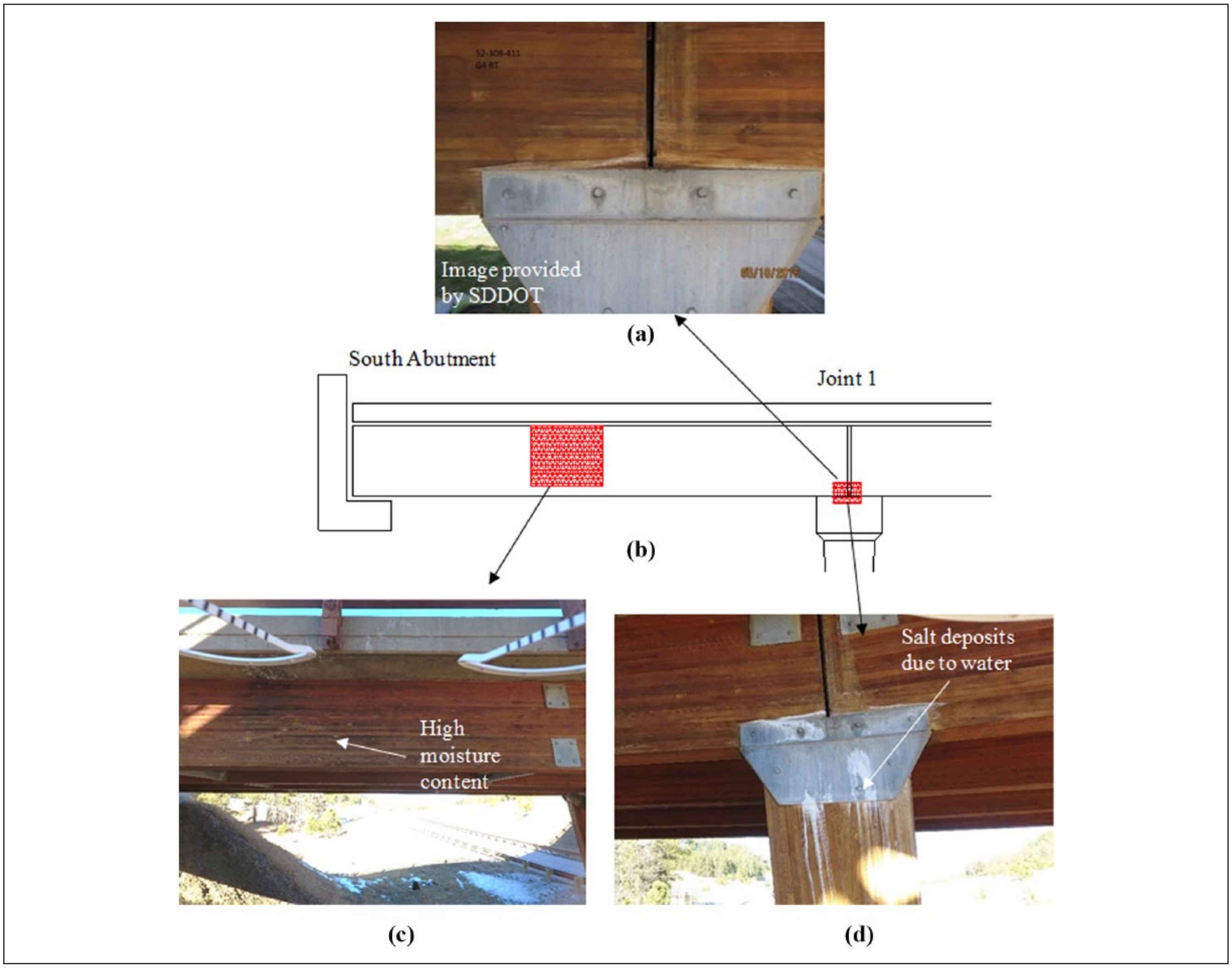

Figure 8. Sample damage on girder: (*a*) image provided by South Dakota DOT (*13*), (*b*) damage location, (*c*) some moisture on the side of Girder 4 between South Abutment and Joint 1, and (*d*) salt deposits caused by water coming from the deck at the support of Girder 4 at Joint 1.

(2-in.) surface scratch on the bottom of Girder 1 between Joints 1 and 2 which was also measured using the data from the UAS.

Conclusions

The following conclusions can be drawn from the literature review, UAS selection, and UAS-based inspection of the selected bridge located in South Dakota.

1. UASs present an efficient alternative for bridge inspection because of their high-resolution cameras and increasing technology development (e.g., OA).
2. Appropriate weather conditions must be considered to safely operate the UAS. For example, calm wind conditions with wind speeds below 15 mph.
3. The UAS used for the selected bridge was able to perform an underside of deck inspection without GPS signal failure. Also, the high-resolution camera mounted on the UAS allowed for a detailed damage identification under the deck while tilted up at an angle of 35 degrees.
4. The UAS was effective in identifying different types of bridge damage, especially for concrete cracks, spalling, and moisture on concrete decking, and salt deposit and moisture on timber glulam girders.
5. The comparison of images captured from the UAS-enabled inspection and traditional inspection methods demonstrated the accuracy of the damage identification using UAS data.
6. The use of UASs can minimize the risk of injury to inspectors, helping to reduce safety concerns during field inspection work. In addition, the UASs allow inspectors to view areas of the bridge not visible during routine bridge inspections.

Challenges

During this study, several limitations, including light conditions on the underside of the deck, high-contrast on sunny days, and some obstacles under the bridge deck, were identified. Such challenges could be overcome by stringent flight and inspection planning to avoid undesirable image overexposure, and attaching additional flashlights to the UAS to enhance the illumination under the deck. It is expected that the DOT will incorporate the use of UASs to supplement routine inspections in the near future.

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References

1. Eschmann, C., C.-M. Kuo, and C. Boller. Unmanned Aircraft Systems for Remote Building Inspection and Monitoring. *Proc., 6th European Workshop on Structural Health Monitoring*, Dresden, Germany, Vol. 2, 2012, pp. 1–8.
2. Koonce, J., T. Demski, M. Rowe, and N. Morriss. *Bridge Inspection Access to Minimize Operational Impacts*. Research Project, Final Report 2015-40. Collins Engineers Inc., Chicago, IL, 2011.
3. Chen, S., C. Rice, C. Boyle, and E. Hauser. Small-Format Aerial Photography for Highway-Bridge Monitoring. *Journal of Performance of Constructed Facilities*, Vol. 25, No. 2, 2011, pp. 105–112.
4. Chen, Z., and T. C. Hutchinson. Image-Based Framework for Concrete Surface Crack Monitoring and Quantification. *Advances in Civil Engineering*, Vol. 1, 2010, pp. 1–18.
5. Khaloo, A., D. Lattanzi, K. Cunningham, R. Dell'Andrea, and R. Mark. Unmanned Aerial Vehicles (UAV) Inspection of the Placer River Trail Bridge through Image-Based 3D Modeling. *Structure and Infrastructure Engineering*, 2017. http://dx.doi.org/10.1080/15732479.2017.1330891.
6. ASCE Infrastructure Report Card. *ASCE News*, 2016.
7. Moller, P. *CALTRANS Bridge Inspection Aerial Robot*. Publication Report No. CA08-0182. Caltrans, 2011.
8. Otero, L. D. *Proof of Concept for using Unmanned Aerial Vehicles for High Mast Pole and Bridge Inspections*. Publication Final Report, DOT, Florida, 2015.
9. Lovelace, B., and J. Zink. *Unmanned Aerial Vehicle Bridge Inspection Demonstration Project*. Publication Report No. MN/RC 2015-40. DOT, Minnesota, 2015.
10. *DJI Phantom 4 Specifications*. DJI Phantom Company. www.dji.com/product/phantom-4/info#specs. Accessed May 23, 2017.
11. Duque, L., J. Seo, and J. Wacker. Synthesis of Unmanned Aerial Vehicle Applications for Infrastructures. *Journal of Performance of Constructed Facilities*, In press.
12. Seo, J., J. Wacker, and L. Duque. Evaluation of Unmanned Aircraft Systems as a Bridge Inspection Tool. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. (currently under review).
13. South Dakota DOT. *Bridge Inspection Report*, South Dakota DOT, USA, 2016.

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