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Drone-enabled bridge inspection methodology and application

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ABSTRACT

The field of Civil Engineering has lately gained increasing interest in Unmanned Aerial Vehicles (UAV), commonly referred to as drones. Due to an increase of deteriorating bridges according to the report released by the American Society of Civil Engineers (ASCE), a more efficient and cost-effective alternative for bridge inspection is required. The goal of this paper was to analyze the effectiveness of drones as supplemental bridge inspection tools. In pursuit of this goal, the selected bridge for inspection was a three-span glued-laminated timber girder with a composite concrete deck located near the city of Keystone in the state of South Dakota (SD). A drone, a Dà-Jiāng Innovations (DJI) Phantom 4, was utilized for this study. Also, an extensive literature review to gain knowledge on current bridge inspection techniques using drones was conducted. The findings from the literature review served as the basis for the development of a five-stage drone-enabled bridge inspection methodology. A field inspection utilizing the drone was performed following the stages of the methodology, and the findings were compared to current historical inspection reports provided by the SD Department of Transportation (SDDOT). Quantified data using the drone such as a spalled area of 0.18 m^2, which is identical to the measurement provided by the SDDOT (0.3 m by 0.6 m), demonstrated the efficiency of the drone to inspect the bridge. This study detailed drone-enabled inspection principles and relevant considerations to obtain optimum data acquisition. The field investigation of the bridge demonstrated the image quality and damage identification capabilities of the drone to perform bridge inspection at a lower cost when compared to traditional methods.

1. Introduction

The American Society of Civil Engineers (ASCE) has regularly studied the structural performance of the nation's infrastructure, including bridges. The most recent ASCE report card for America's infrastructure, released in December 2016, specified that approximately 9.1% of the nation's bridges were classified as structurally deficient for a letter grade of C^+ [1]. Although the number of deficient bridges has declined from 11% to 9.1% in the last three years [2], there is a need for a more efficient and affordable technique to visually inspect bridges. In fact, the use of drones has become more attractive to bridge owners, researchers and stakeholders due to their ability to gather critical information in less time and at a lower cost when compared to traditional inspection techniques.

Numerous research efforts [3–5] have been made to develop new techniques to monitor and inspect infrastructure. Drone technology has shed light on how to overcome time consuming, risky, and relatively expensive bridge inspection practices. For instance, Chan et al. [3] conducted a study on drone-based inspection compared to conventional inspection practices. To complete the study, several considerations were made concerning drone capabilities for bridge inspection, inspection requirements, cost-benefit analysis, and challenges of aerial platforms. It was concluded that drones have some advantages over conventional inspection practices including cost, time, reduced risk for inspectors, and inspection quality. A more in-depth study of structure inspection was conducted by Koch et al. [5]. During this study, the authors performed an analysis of large concrete structures, including bridge columns. To conduct the analysis, different inspection techniques, such as 3D surface reconstruction, were implemented to identify damage. The authors concluded that the drone-enabled inspection coupled with vision-based technology had potential to serve as a more economical and safe alternative to conventional inspection practices. It can be seen that drone technology has helped inspectors conduct visual assessment of infrastructure at a low cost and with less injury risk when compared to conventional inspection methods.

The primary goal of this research was to evaluate the capabilities of the drone technology as a supplemental bridge inspection tool to support legally mandated conventional bridge inspections. To that

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end, a selected bridge located near Keystone, South Dakota (SD) was inspected following state and federal regulations (i.e., SD Department of Transportation (SDDOT) and Federal Aviation Administration (FAA)). This paper is subdivided into five sections, including this section. The second section presents the selected drone and bridge for this study. The third section details the developed bridge inspection methodology, while the fourth section discusses the application of the methodology to the selected bridge in accordance with the state and federal regulations. The fifth section presents a comparison of results between drone-based and conventional bridge inspection. The final section provides conclusions and challenges during bridge inspection using drone technology.

2. Drone and bridge selection

This section is dedicated to the discussion of the drone and bridge selection; thus, the results of the selection process are presented in the following subsections.

2.1. Selected drone

The drone to conduct this study was chosen based upon different considerations including flight time, upward viewing camera, camera resolution, video resolution, and others. A number of researchers have utilized and studied a variety of drones to determine their proficiencies in terms of data gathering for bridge inspection. A total of 13 different drones were investigated (see Table 1) to efficiently select a suitable drone for bridge inspection. To efficiently select a drone, the following seven considerations were studied.

(1) **Flying time over 20 min**: longer inspection time allows for a more efficient and comprehensive bridge inspection as it minimizes interruptions to change the drone batteries;
(2) **Additional camera on top of drone**: the ability to observe directly under the deck permits a more detailed inspection;
(3) **Camera resolution with low illumination**: due to lack of illumination under the deck, the drone camera must be able to capture high-resolution images under low illumination. It can be noted that the illumination can be enhanced by additional flashlights either attached to the drone or located on the ground;
(4) **Video resolution**: aside from still images, the drone must be able to record high-definition videos to perform video-based inspection as needed;
(5) **Payload capacity**: payload is important as it allows the drone to carry additional attachments such as flashlights or cameras if needed;
(6) **Drone lights**: the drone Light-Emitting Diode (LED) lights included on some drones serve as a source of illumination and should be considered to provide extra illumination required for efficient damage observation underneath a bridge; and
(7) **Remote range**: some structures are located over water or are not accessible by inspectors. Therefore, a long-range remote control is required to inspect such structures.

Considering the aforementioned specifications, a total of four drones were deemed suitable for bridge inspection. The selected drones included the DJI Matrice 100, DJI S900, DJI Phantom 3 pro, and DJI Phantom 4. Among the suitable drones, the DJI Phantom 4 (see Fig. 1) was selected over the others due to its performance and versatility meeting the considered requirements at a reasonable cost. The intent of selecting an affordable drone was to provide a viable and cost-efficient alternative to current inspection practices that can be implemented by county-level administrations. Additional technology, which is Obstacle Avoidance (OA), allows the drone to avoid harm to both bridge and drone components along with persons and property. Another consideration was the ability to fly in manual mode to avoid Global Positioning System (GPS) signal under the bridge. It should be noted that drone technologies have rapidly grown in recent years; thus, their costs and features will change quickly over time.

2.2. Selected bridge

A glued-laminated girder bridge with a composite concrete deck was selected, as seen in Fig. 2. It can be noted that the bridge was selected based on the requirements from the project sponsor, the United States Department of Agriculture – Forest Products Laboratory (FPL). The bridge was located on US16 to US16A Highway, near the city of Keystone in Pennington County, SD. The bridge had three simply supported spans with four girders spaced at 2.3 m (7.5 ft.) on center (o.c.) and a clear width of 7.9 m (26 ft.). The bridge was horizontally curved at an estimated radius of 116.4 m (881.97 ft.) and is a 51.8 m (170 ft.) long with steel guardrails along the edges of the superstructure.

3. Bridge inspection methodology

Due to a lack of systematic damage identification and drone inspection procedures, a five-stage bridge inspection methodology that allowed for an efficient drone-enabled bridge inspection (see Fig. 3) was developed. The methodology was based on holistic information related to drone limitations, drone operation conditions, and data acquisition methodology. State and federal regulations were also considered. The methodology is detailed below:

Stage 1 is to complete the *Bridge Information Review*. Information, such as as-built plans, historical inspection reports, and other applicable documents, should be studied in this stage to ensure a complete inspection of the bridge structure. For instance, the review of the inspection reports allows a pilot to identify critical inspection locations (e.g., deck or girders) prior to the drone-enabled inspection. The information gained during this stage permits the pilot to develop flight strategies under limited bridge approachability conditions, identify current damage, and monitor or update critical damage such as concrete cracks on the target bridge.

Stage 2 is to perform a thorough *Site Risk Assessment* of the bridge's surrounding areas. This stage is intended to identify potential risks such as near trees or traffic lanes to safely proceed with the drone-enabled inspection. Other benefits of performing a site risk assessment prior to conducting the inspection include identification of safe landing/take off zones, safe bridge approaching areas, and pilot risk minimization. Additionally, state and federal regulations should be accounted for prior to establishing a flying strategy. Regulations vary from location to location; it is advised to confirm with DOTs and the FAA to identify potential applicable restrictions for the bridge location. Finally, to ensure pilot safety, traffic control mechanisms, such as warning signs near the pilot, should be implemented.

Stage 3 is to perform the *Drone Pre-flight Setup*. It is recommended, by both the FAA and drone manufacturers, to conduct a thorough inspection of the drone prior to the first flight of the day. Inspections of all the software and hardware including, but not limited to, propellers and rotors, battery levels of all instruments (e.g., a remote controller,

Table 1
Comparison of identified drone specifications [21].

Drone	Price	Approximate fly time	Upward camera view	Camera resolution with low illumination	Video resolution	Payload capacity	Another source of light	Remote range	Satisfactory[a]
DJI Inspire 1 [6]	$2000	18 min	94-degree vertical range	Optional flashlight attachment will improve quality	4 k/1080p	1700 g	Drone have red LED lights	6562 ft	3
Voyager 3 [7]	$2000	25 min	Facing upward at an angle	Optional flashlight attachment will improve quality	1080p	320 g	Drone have red and blue LED lights	3281 ft	2
DJI Matrice 100 [8]	$2800 to $3300 + $750 for camera	40 min	Need to buy camera	Optional flashlight attachment will improve quality	1080p	1000 g	Drone have green LED lights	16,404 ft	4
DJI Phantom 3 Pro [9]	$1200 + $499 for GoPro camera	23 min	94-degree vertical range[b]	Optional flashlight attachment will improve quality	4 k/1080p	462 g	Drone have red and yellow LED lights	16,404 ft	4
DJI Phantom 4 [10]	$1800 + $499 for GoPro Camera	28 min	94-degree vertical range[b]	Optional flashlight attachment will improve quality	4 k/1080p	462 g	Drone have red and yellow LED lights	16,404 ft	4
Yuneec Typhoon H [11]	$1600	25 min	Facing upward at an angle	Optional flashlight attachment will improve quality	4 k/1080p	600 g	Drone have green, red and blue LED lights	3281 ft	3
DJI S900 airframe [12]	$3000 + $750 to $1300 for camera	20 min	Optional attachment	Optional flashlight attachment will improve quality	4 k/1080p	4300 g	No LED lights	3281 ft	4
Yuneec Typhoon 4K [13]	$1100	25 min	115-degree vertical range	Optional flashlight attachment will improve quality	1080p	600 g	Drone have red and yellow LED lights	2625 ft	3
Blade Chroma [14]	$700	30 min	Facing upward at an angle	Optional flashlight attachment will improve quality	4 k/1080p	200 g	Drone have green, red and blue LED lights	1312 ft	2
Autel Robotics X-Star Premium [15]	$900	25 min	108-degree vertical range	Optional flashlight attachment will improve quality	4 k/1080p	180 g	No LED lights	6562 ft	2
SenseFly eBee [16]	$25,000	50 min	No	Optional flashlight attachment will improve quality	1080p	NA	No LED lights	9843 ft	1
SenseFly albris [17]	$45,000	22 mi	Yes	Flashlight included	4 k/1080p	NA	Drone have green, red and blue LED lights	6562 ft	5
Topcon Sirius Pro [18]	$53,000	55 min	No	Optional flashlight attachment will improve quality	1080p	NA	No LED lights	9843 ft	1

GoPro camera to look straight up USD $499, total weight approximately 200 g including mount.
GoPro camera mount to attach to drone (included with camera or additional mount can be bought for USD $29.99).
[a] Rated 1–5 with 5 being the highest score.
[b] Attachments.

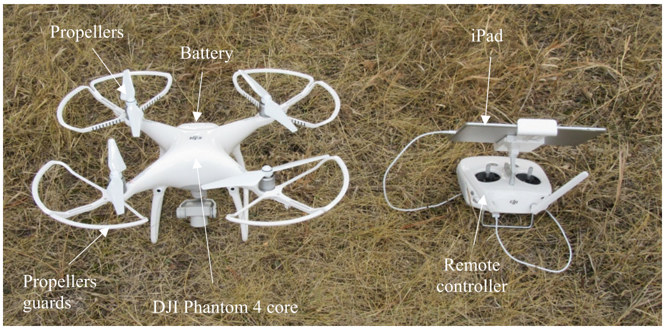


Fig. 1. Image of the DJI Phantom 4 (taken by Junwon Seo).

storage batteries, and a monitor), remote controller, gimbal, and firmware updates should be conducted. A compass calibration must be performed prior to flying at a new location to prevent GPS signal loss during a flight.

Stage 4 is to complete the *Drone-Enabled Bridge Inspection*. Once all the preliminary information has been gathered during the previous stages, the inspection using the drone can be conducted. During the operation of the drone, it is necessary to consider weather conditions such as wind, as it can negatively affect the performance of the drone. Aside from weather conditions, the inspection plan should be performed as planned to avoid delays or damage to both the structure and the drone. It is recommended to first capture the overall sections of the bridge and then to gather close-up or detailed information of each structural and non-structural component. It can be noted that current regulation does not allow drone operation over traffic; thus, the inspection of some sections (i.e., with location over roadway) should be conducted from afar. Finally, per FAA regulations, the Pilot-in-Command (PIC) should be continuously assisted by an observer to avoid distractions and possible accidents.

Stage 5 is to complete the *Damage Identification*. For a successful drone-based bridge inspection, the damage should be easily identified from the gathered information. The images captured using the drone serve as the basis for further computational analysis including photogrammetry-based inspection. The use of 3D photogrammetric virtual models serves as an overview of the damage compared to conventional 2D images. The reconstruction of 3D virtual models could be completed in a computer software, such as PhotoScan. To construct the 3D virtual model, PhotoScan will need images taken by the drone that can represent points enabling a 3D view of the target structure. Then, using a triangulation technique to connect the points, PhotoScan can generate the surface for a more detailed view and make a texture and color correction. This process is able to provide a visual representation of the target structure in a 3D virtual space.

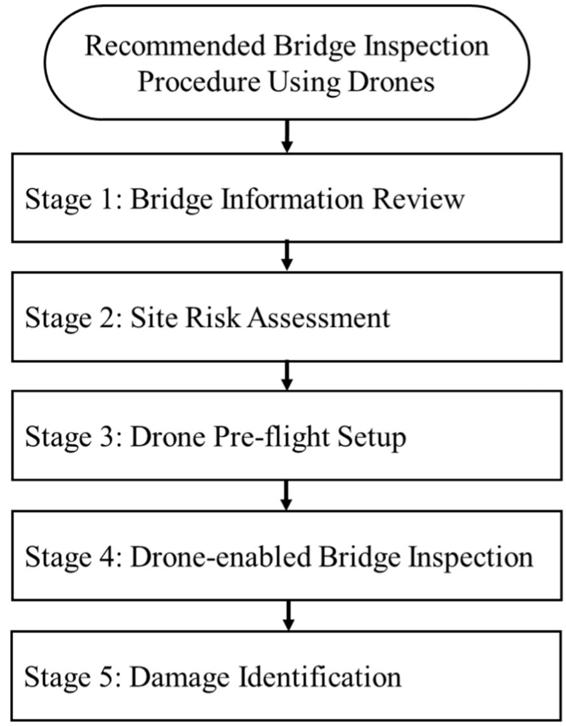


Fig. 3. Recommended five-stage bridge inspection methodology using a drone.

4. Application of inspection methodology to timber girder bridge

The following section presents the inspection conducted on the selected bridge in accordance with the proposed five-stage bridge inspection methodology.

4.1. Stage 1

During the *Bridge Information Review*, critical information regarding the bridge structure was determined. Based upon the inspection report provided by the SDDOT, it was found that the deck joints were the most critical component due to water leakage coming from the deck surface. After determining the critical inspection zones, the study of the as-built plans was completed. The information regarding the location and dimension of the bridge components allowed for a more efficient inspection of the bridge components. During the inspection, the component numbering was followed based on the construction plans as seen in Fig. 4. After the review of all the documentation, an inspection plan was developed to inspect the bridge using the drone. To complete the

Fig. 2. Glulam timber girder bridge overview taken by the drone.

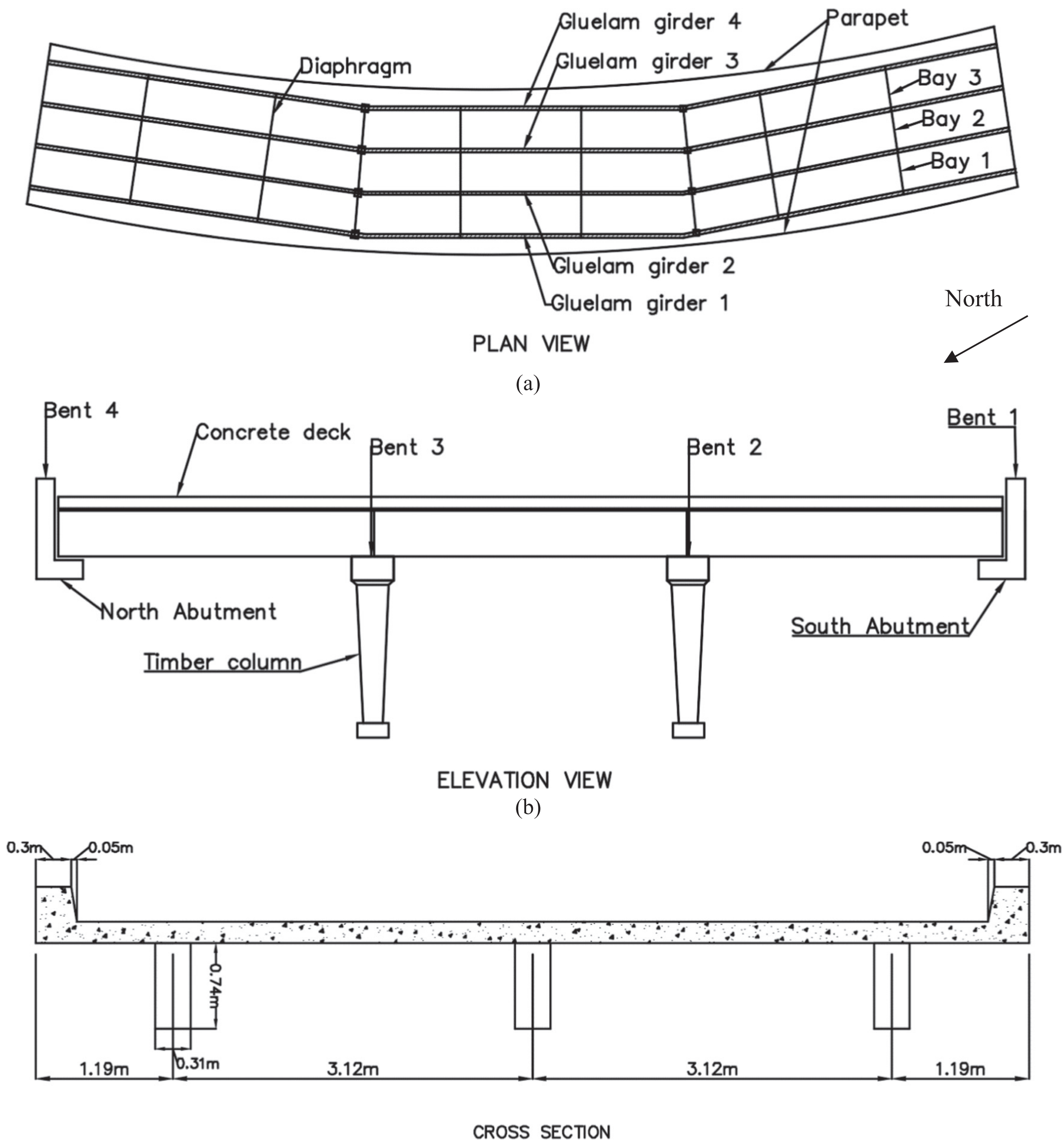


Fig. 4. Glulam timber girder bridge components numbering: (a) component numbering on plan view; (b) component numbering on elevation view; and (c) cross-section view.

inspection, it was established that a general bridge view should be inspected first, and then more detailed structural components, such as girders, columns, and underside of deck, can be captured for a more comprehensive data gathering.

4.2. Stage 2

A comprehensive *Site Risk Assessment* of the surrounding and bridge were conducted to determine potential risk zones for the operation of the drone. Two potential critical inspection areas were identified based on the geometry of the bridge and adjacent structures as seen in Fig. 5. The identified critical inspection areas were defined as the location of restricted access for the operation of the drone to obtain overview and close-up views of the bridge; they were caused by the adjacent bridge and trees. Fortunately, the bridge was not located in a high-risk zone, despite limited operation space in the identified critical inspection areas, as there was not a large amount of trees near or over the bridge.

The SDDOT stated that no drone operation over the deck was allowed. Other recommendations from SDDOT included traffic control warning signs near inspectors and liability insurance (i.e., Verifly) to protect both the drone and the bridge structure in case of an accidental flyaway. Further, FAA specific regulations, such as flying within five

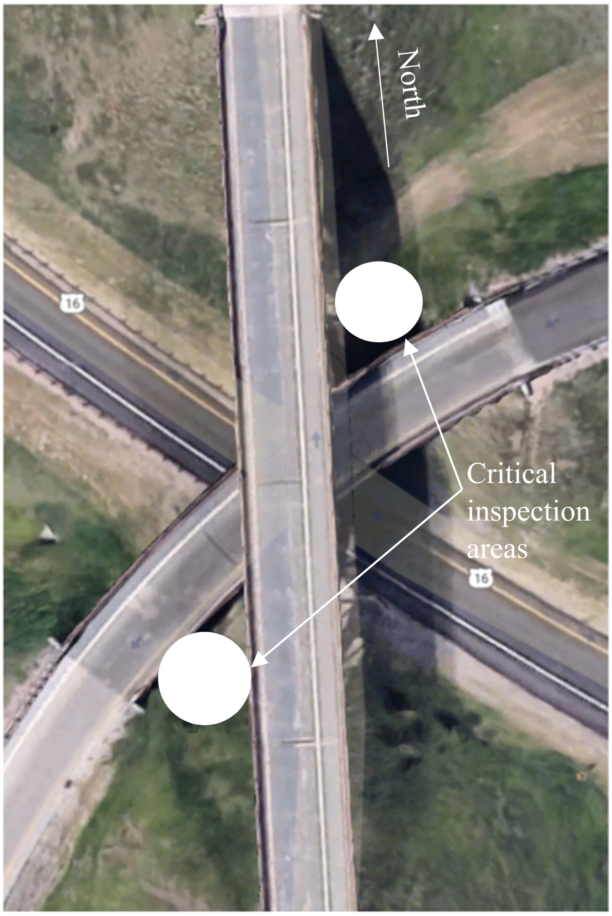


Fig. 5. Critical bridge inspection areas (extracted from Google Maps).

miles of an airport, did not apply to this bridge location. In detail, general FAA part 107 regulations for drone operation include the following [19]: 1) no restriction for Class G airspace, need air traffic control tower permission otherwise; 2) must keep the aircraft in sight (visual line-of-sight); 3) must fly under 400 ft; 4) must fly during the day; 5) must fly at or below 100 mph; 6) must yield right of way to manned aircraft; 7) must not fly over people; and 8) must not fly from a moving vehicle.

4.3. Stage 3

Prior to the inspection of the bridge, a *Drone Pre-Flight Setup* must be completed. As previously mentioned, the DJI Phantom 4 was selected. It is recommended by both the FAA and DJI to perform a thorough inspection of the platform prior to the first flight of the day. To conduct the drone's inspection, all the components and software were inspected including rotors, propellers, batteries, iPad, remote controller, gimbal, and software updates to ensure flight safety. The components were found to be in excellent condition, minimizing potential failure during the inspection. Finally, the compass of the drone was calibrated to ensure full GPS support during the flight. The calibration was performed using two drone rotation movements. First it was rotated counter clockwise while being held horizontally as shown in Fig. 6a. Then the same rotation was executed with the drone being held vertically and the camera facing down as seen in Fig. 6b.

4.4. Stage 4

The *Drone-Enabled Bridge Inspection* was completed after all the precautionary actions detailed in Stages 1 through 3 were considered. To perform the inspection, the preplanned scheme of capturing general views of the bridge first and then obtaining close-up views was followed as demonstrated in Fig. 7a and b. The inspection of the bridge was conducted over the course of two days. The weather

(a) (b)

Fig. 6. DJI Phantom 4 compass calibration demonstration: (a) drone camera horizontally rotating counterclockwise and (b) drone camera facing down rotating counterclockwise (taken by Callie Duque using digital camera).

Fig. 7. Sample images obtained from the timber girder bridge inspection: (a) glulam girder bridge overview (taken by Junwon Seo using drone); (b) damage on timber girder bridge (taken by Luis Duque using drone); and (c) drone flying near girder (taken by Junwon Seo using digital camera).

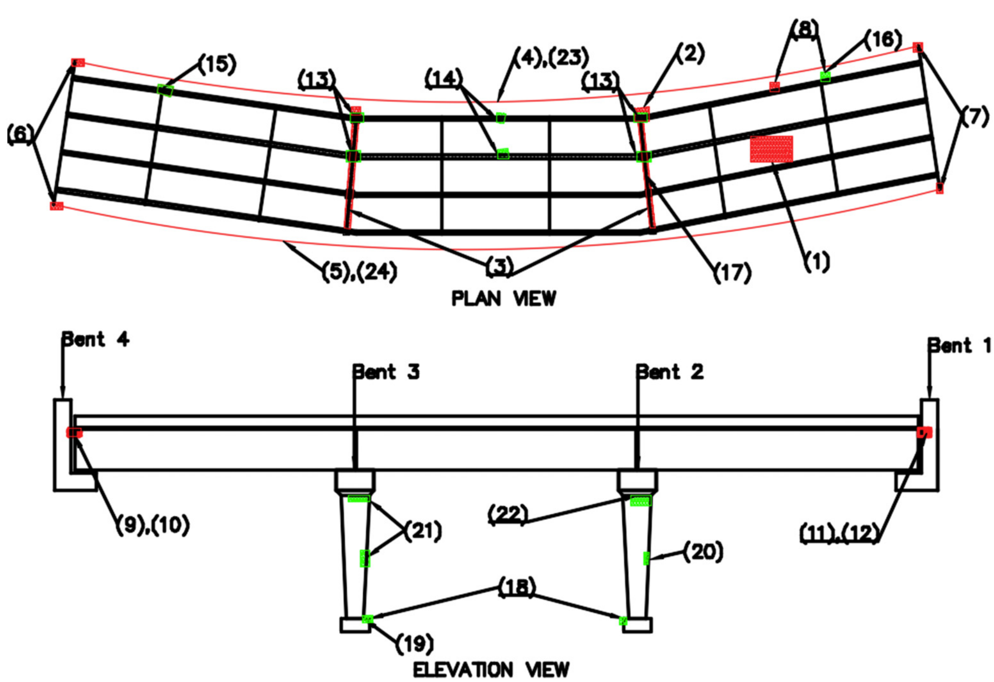


Fig. 8. Timber girder bridge layout with identified damage.
Note: red marks in plan and elevation views indicate concrete damage, green marks represent timber damage. Also, red lines in plan view denote minor cracks along the parapet and rusting in railing in a longitudinal direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 9. Underside of deck sample damage gathered using drone (taken by Junwon Seo): (a) concrete spalling and corrosion with exposed rebar near Girder 4 at Joint 1; (b) concrete spalling near Girder 4 at Joint 3; and (c) 3D virtual model of Joint 2 near Girder 4 using PhotoScan.

conditions were favorable during the first day of inspection with wind speeds under 10 mph. The favorable weather conditions allowed the inspectors to capture details of structural components to identify damage, such as concrete cracks and corrosion. On the other hand, during the second day of inspection, the weather conditions were not as favorable with wind speeds of 15 mph and wind gust of over 25 mph. Due to the high wind speeds, a video-based data acquisition approach was considered to minimize distractions from the picture-taking process. Further, the PIC was continuously assisted by an observer, especially during the second day when the flying conditions were not ideal. After concluding the inspection, it was established that the video-based data acquisition, with additional post-processing to gather still images, could potentially reduce the risk of drone crashing and simplify damage identification.

4.5. Stage 5

The final stage for the drone-enabled bridge inspection was to

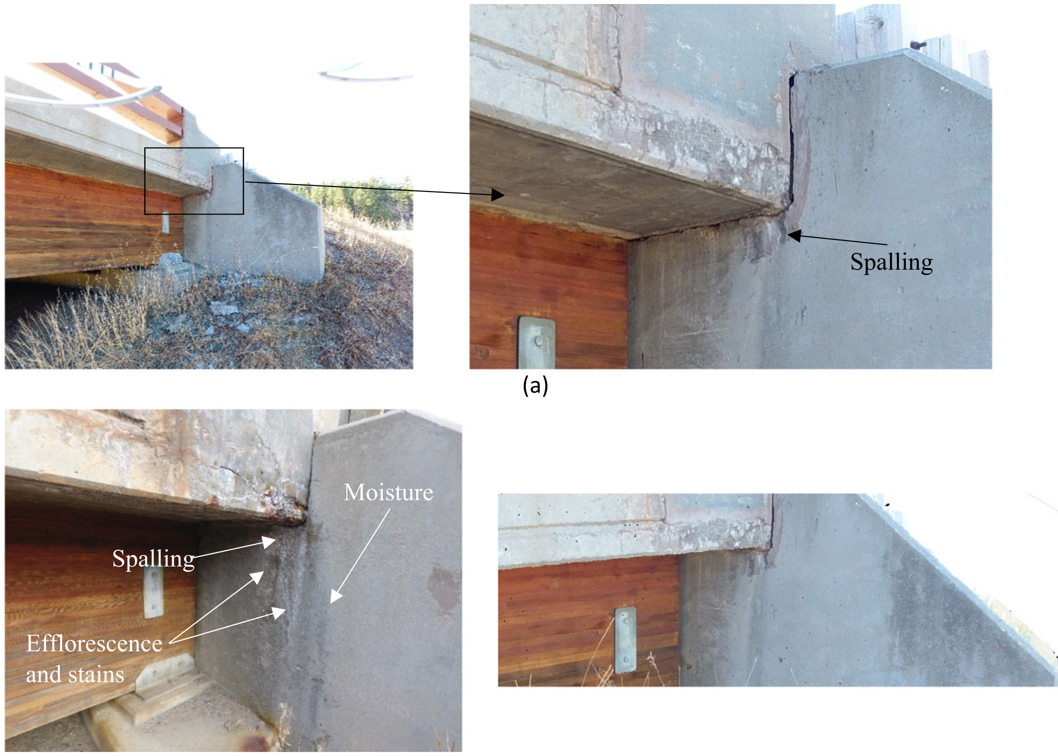


Fig. 10. Sample abutment damage detected using drone (taken by Luis Duque): (a) Spalling on South Abutment near Girder 1; (b) spalling and discoloration of concrete caused by moisture at North Abutment near Girder 4; and (c) 3D virtual representation of South Abutment near Girder 1.

conduct the *Damage Identification*. Sample results for the Underside of Deck, Abutment, and Girder damage are presented to demonstrate the quality of data obtained using the drone. Using a photogrammetric computer software, PhotoScan, the structural components were recreated in 3D virtual space to observe the damage from different angles. The schematic shown in Fig. 8 shows all the identified damage on the bridge found using the drone.

4.6. Underside of deck

In general, the inspected deck had a large amount of moisture-related damage at the joints (see Fig. 9a and b) as expected from the historical inspection reports. Fig. 9a shows concrete spalling and exposed rebar near Girder 4 at Joint 2, and Fig. 9b presents concrete spalling and delaminations near Girder 4 at Joint 3. Further, a representation of the damage near Girder 4 at Joint 2 was created using PhotoScan to create a 3D virtual model in order to better visualize it in 3D virtual space as seen in Fig. 9c.

4.7. Abutment

The abutments were in overall good condition. Only minor damage, such as cracking and discoloration, was observed during the drone-enabled inspection as seen in Fig. 10a and b. Fig. 10a shows spalling on the South Abutment near Girder 1, and Fig. 10b displays spalling, efflorescence, and moisture on the North Abutment near Girder 4. Additionally, using PhotoScan, the damage on the South Abutment near Girder 1 was successfully recreated in 3D virtual space as seen in Fig. 10c.

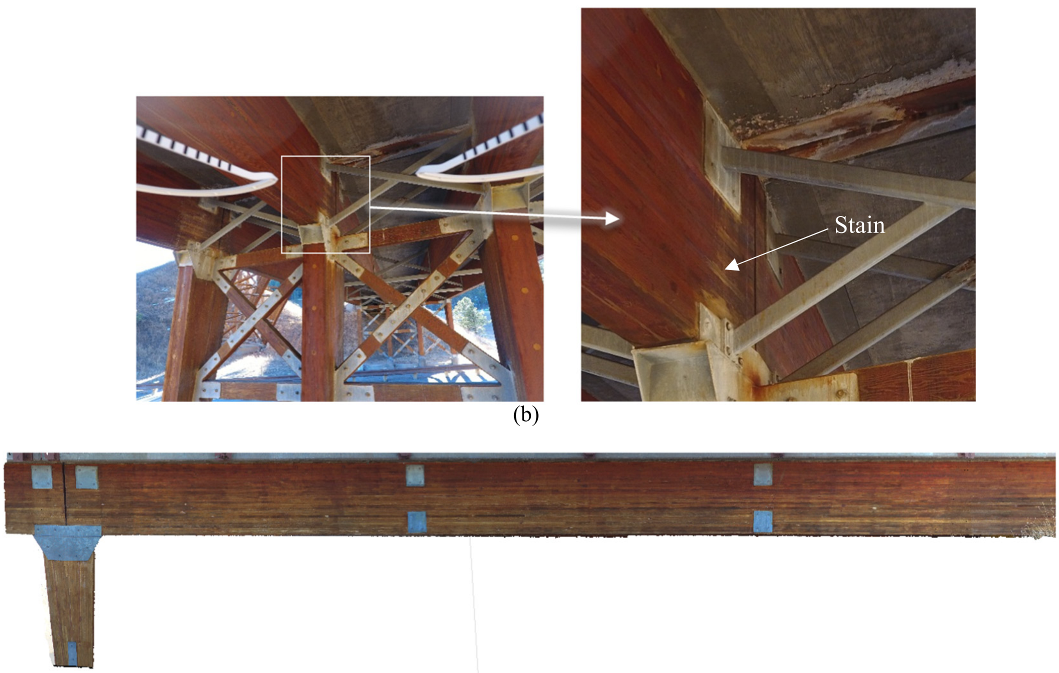
4.8. Girders

Overall, the girders were in good condition despite some minor water damage caused by water coming from the deck. In detail, the ends of the girders presented some stains and discoloration possibly caused by calcium deposits from the chemical reaction between salt, water, concrete, and steel, especially during the winter season. Sample images of the identified damage can be seen in Figs. 11a and 12b. Fig. 11a shows high moisture on Girder 4 between Joints 3 and 4, and Fig. 11b illustrates stains due to water leakage from the deck. With the aid of PhotoScan, Girder 4 between Joints 3 and 4 was successfully recreated in 3D virtual environment.

5. Comparison to conventional inspection methods

After all the damage was identified, a side-by-side comparison between the drone-enabled bridge inspection and conventional inspection techniques was performed. The schematic presented in Fig. 8, accompanied by the side-by-side comparison of each identified damage on Table 2, aimed to provide a simplified and detailed comparison between the two methods. Images obtained using the drone for the sample structural components, including underside of deck, abutments, and girders, were also compared to images provided by SDDOT for a visual comparison.

(a)



(b)

(c)

Fig. 11. Sample girder damage detected using the drone (Taken by Luis Duque): (a) moisture damage on the side of Girder 4 between Joints 3 and 4; (b) stains on the side of Girder 3 at Joint 3; and (c) 3D virtual representation.

5.1. Underside of deck

The inspection report developed based on the drone-enabled bridge inspection findings coincided with the damage reported by the SDDOT. As expected, damage, such as concrete spalling, corrosion, and exposed rebar, was observed near joints due to water leakage from the surface of the deck. A visual comparison of images provided by the SDDOT to those gathered using the drone can be seen in Fig. 12. The image provided by the SDDOT is shown in Fig. 12a to provide a visual comparison to those taken using the drone as seen in Fig. 12c and d. It is evident that the images are of similar quality, and for the underside of deck, the drone was able to capture a closer view. In terms of quantifiable damage, the SDDOT identified a 0.3 m by 0.6 m spalled area with exposed rebar at Joint 2. Throughout a damage pixel-based method, the spalled area measurement was determined to be 0.18 m^2. Both measurements are identical, confirming the accuracy of the UAV-based inspection.

5.2. Abutments

Overall, the abutments were in good condition and the identified damage (see Fig. 13a) coincided with the inspection report provided by SDDOT. No major damage was observed other than some minor damage, such as cracking, spalling, and discoloration on the South Abutment (see Fig. 13b) and discoloration and water leakage on the North Abutment (see Fig. 13c). It can be noted that there were no images provided by the SDDOT to be compared for the abutments. It also can be noted that the SDDOT did not included any quantifiable data for the Abutment damage.

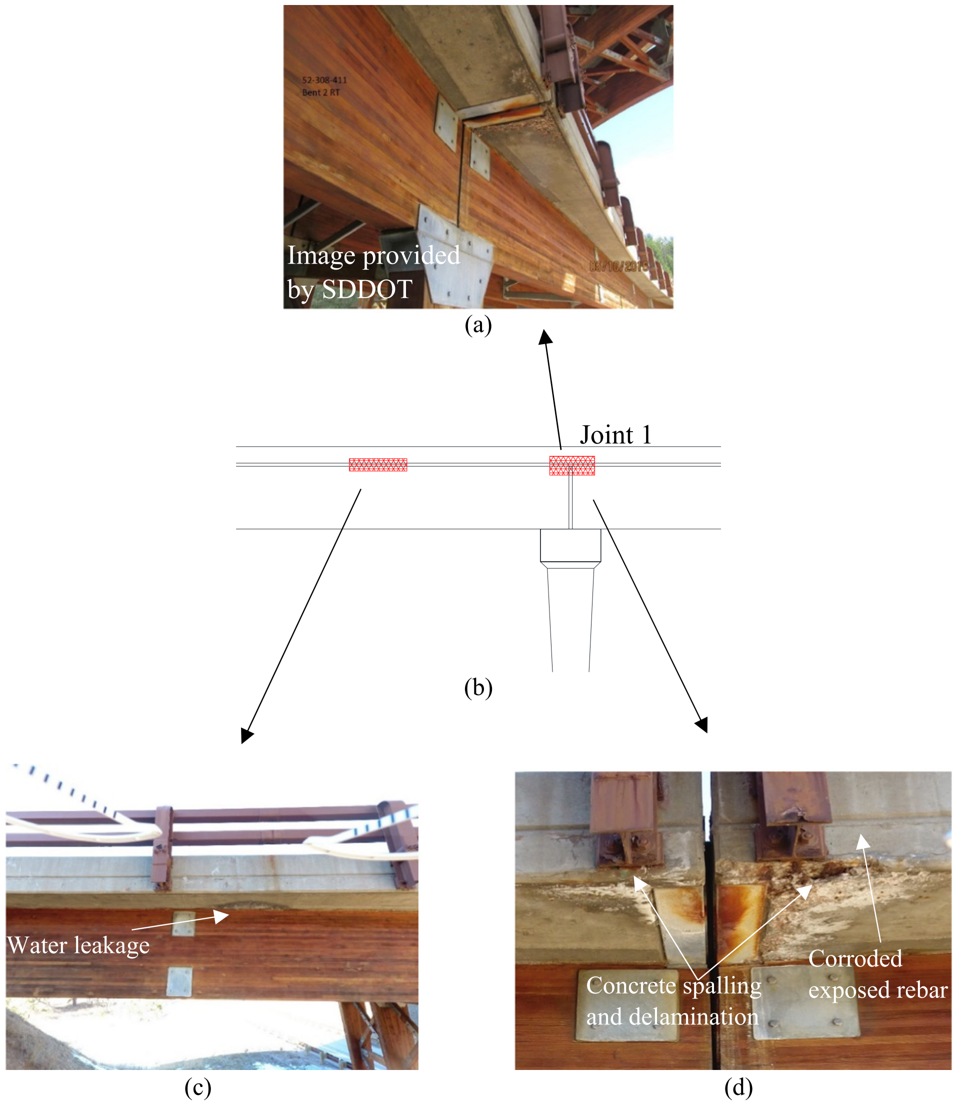


Fig. 12. Comparison of results between drone-enabled and conventional inspections: (a) image provided by SDDOT [20]; (b) damage locations [20]; (c) water leakage under deck between South Abutment and Joint 1 (taken by Luis Duque using drone); and (d) concrete spalling and corrosion with exposed rebar near Girder 4 at Joint 1 (taken by Luis Duque using drone).

5.3. Girders

The identified damage on the girders reported by SDDOT was observed using the drone. Fig. 14a shows an image provided by the SDDOT to be compared to drone-enabled images (see Fig. 14c and d). The images gathered using the drone were of comparable quality to the one provided by SDDOT, confirming the ability of the drone to obtain high-quality data for damage identification. Note that some damage, such as moisture on Girder 4 between Joints 1 and 2 and Girder 4 between Joints 3 and 4, was not specified by the SDDOT. This damage must have been recent and demonstrated the importance of frequent routine inspections using drones to evaluate the damage and prevent unrepairable structure failure. Lastly, the SDDOT did not include quantifiable data for the bridge inspection aside from a 5.08 cm (2 in) by 5.08 cm (2 in) surface scratch on the bottom of Girder 1 between Joints 2 and 3. This damage was also measured using the UAV images.

6. Conclusions and challenges

This study aimed to investigate the capabilities of the drone to conduct bridge inspection related activities. To complete this study, the inspection of an in-service timber girder bridge structure was completed using the DJI Phantom 4 aerial platform. In addition, the five-stage recommended drone-enabled bridge inspection methodology was developed for a more efficient inspection procedure and to aid next generation bridge inspections. The drone's capabilities to complete bridge inspection tasks were studied in terms of image quality and damage identification. A side-by-side comparison of the damage detected using the drone and inspection reports provided by the SDDOT

Table 2
Comparison of SDDOT inspection report and drone-enabled inspection report for timber Girder bridge.

Structural component	SDDOT inspection report	Drone-enabled inspection report	Comparison
Underside of deck	Near Stringer 1 at Joint 2: cracking delamination, and discoloration	(1) Bay 2 between Joints 1 and 2: white efflorescence	There are no major differences between the damage reported by SDDOT and the drone-enabled inspection report. minor differences include water damage between spans captured using the drone and not reported by SDDOT.
	Bays 2 and 3 at Joint 2: joint cracking and minor scaling	(2) Near Girder 4 at Joint 2: corroded exposed rebar, spalling, delamination, and efflorescence	
	Bays 2 and 3 at Joint 3: joint scaling, cracking, and delamination	(3) Along Joints 2 and 3: corrosion, spalling, delamination, and discoloration	
	Near Girder 1 parapet along entire deck: has cracking and discoloration	(4) Near Girder 4 Parapet along entire deck: minor cracks and discoloration especially near railings	
	Near Girder 4 parapet along entire deck: scaling, cracking, delamination, and efflorescence	(5) Near Girder 1 Parapet along entire deck: minor cracks and spalling especially near railings	
	Near Girder 4 at Joint 4: spalling and exposed rebar	(6) Near Girders 1 and 4 at Joint 4: concrete cracking, spalling, exposed rebar, discoloration, and water damage	
	Near Girder 4 at Joint 1: cracking, discoloration, and efflorescence	(7) Near Girders 1 and 4 at Joint 1: cracking and discoloration	
	Bay 2 at Joint 4: Scaling, delamination and efflorescence in Bay 2	(8) Near Girder 4 between Joints 1 and 2: water leakage	
Abutment	North Abutment near Girder 1: is spalled off and has exposed rebar	(9) North Abutment near Girder 1: spalling and corroded exposed rebar	There are no major differences between the damage reported by SDDOT and the drone-enabled inspection report.
	North Abutment near Girder 1: spalling	(10) North Abutment near Girder 4: cracking, efflorescence, rust stains, and water damage	
	South Abutment near Girder 4: efflorescence, scaling, and spalling	(11) South Abutment near Girders 1 and 4: spalling, efflorescence, and moisture	
	South Abutment on Bays 1 and 2: scaling and spalling	(12) South Abutment on Bays 1 and 2: concrete spalling	
Girder	At supports at Joints 2 and 3: bottom of girders has discoloration and decay due to trapped water and debris	(13) Girders 3 and 4 at Joints 2 and 3: bottom surface on both girders has discoloration and stains due to water leakage	Moisture damage between bents was identified using the drone but not reported by SDDOT.
	Girder 3 at Joint 3: surface scratch	(14) Girders 3 and 4 between Joints 2 and 3: stains at bottom of both girders	
	N/A	(15) Girder 4 between Joints 3 and 4: some moisture	
	N/A	(16) Girder 4 between Joints 1 and 2: some moisture	
Diaphragms	Diaphragms have slight discoloration where water has been present	(17) No major issues were found apart from minor discoloration near joints due to water leakage	No difference.
Column	Pedestals at Bent 2: horizontal crack along Bay 2 pedestal wall and crack along top of left side of Column 3 pedestal	(18) Column 4 Pedestal at Bents 2 and 3: minor spalling, cracking, and efflorescence	No major differences other than minor cracks observed on the columns which were not included in the SDDOT report.
	Pedestals at Bent 3: spalling with expose rebar on right side of pedestal and vertical cracks at top left side of Column 3 and left side of Column 4	(19) Column 1 Pedestal at Bent 3: minor spalling and exposed rebar	
	Column 4 pedestal at Bent 2: horizontal crack	(20) Columns 2, 3, and 4 at Bent 2: minor cracks	
	Pedestal wall Bay 2 at Bent 2: longitudinal crack on top	(21) Column 4 at Bent 3: minor cracks and stains on top	
	N/A	(22) Column 4 at Bent 2: stains on top	
Railing	Paint is peeling due to heavy rust in locations throughout, especially on the Railing near Girder 4.	(23) Heavy rusting on Railing at different sections near Girder 4	No difference.
		(24) Mild rusting on Railing near Girder 1	

Note: numbering of drone-enabled inspection report corresponds to damage location in Fig. 8 and N/A indicates Not Applicable.

was conducted. Based on the results obtained, the following conclusions can be drawn from this study.

1. High resolution cameras of the drone, combined with image processing software, such as PhotoScan, proved to be an efficient tool to identify damage on different structural components of the bridge. The use of the photogrammetry software allowed for a more comprehensive and detailed view of damage.
2. During the inspection of the bridge, the drone performed appropriately while flying under the deck despite concerns regarding GPS signal failure. It is noteworthy that the strong GPS signal helps keep the drone stable even at a high wind speed. In addition, the

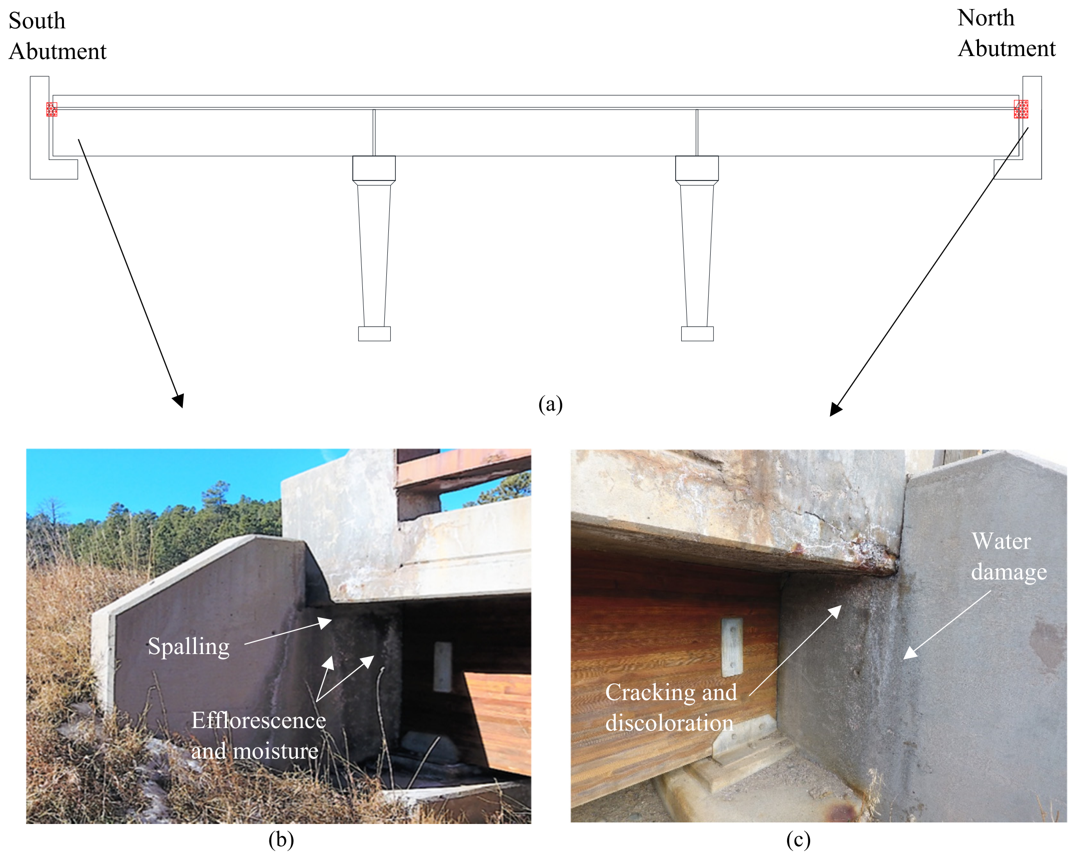


Fig. 13. Sample damage on Abutment: (a) schematic of damage location on abutment; (b) damage on South Abutment near Girder 4 (taken by Luis Duque using drone); and (c) damage on North Abutment near Girder 4 (taken by Junwon Seo using drone).

inspection of the underside of the deck was completed without issues with the camera tilted up at an angle of 35°. It can be noted that the DJI Phantom 4 has the camera under the main body, which initially caused concerns regarding sufficient damage observation above the platform.

3. The drone was able to identify a variety of damage types, including cracking, spalling, corrosion, and moisture on the bridge. The identified damage was observed on timber, concrete, and steel, demonstrating the versatility of the drone to identify a wide range of damage types on different materials.
4. The side-by-side comparison between the drone-enabled bridge inspection report and the results obtained from the inspection reports provided by the SDDOT further established the efficiency of the drone to identify damage on the bridge. Critical damage such as spalling was observed and quantified as 0.18 m^2, which is identical to the measurement provided by the SDDOT (0.3 m by 0.6 m).
5. The proposed methodology can be implemented in routine inspection to access areas of the bridge otherwise not visible to inspectors. It is worthwhile to note that inspectors should be guided to conduct preliminary drone inspection work differently under various weather conditions, including low or moderate wind and sunny or cloudy days, prior to the methodology implementation.

During the conduction of the study, some limitations were largely identified to be caused by unfavorable weather conditions affecting the performance of the aerial platform. The identified limitations included, but were not limited to: [2] high wind speeds, [1] camera overexposure due to sun or snow, [15] low-illumination under the deck, [3] limitations on where the drone could operate due to DOT and FAA rules, and [8] flight challenges due to obstacles in an enclosed section (e.g., between closely spaced girders). Despite the challenges, the drone has great potential to supplement conventional bridge inspection methods and proved to be efficient in identifying different types of damage on specific components of the target bridge.

7. Future research

Although the proposed drone-enabled inspection methodology was able to identify different types of damage for a particular timber bridge in a more efficient fashion than conventional inspection methods, this should be applied to different bridge types. In addition to evaluating different bridge types using drone technology, it is recommended that the damage identified on the bridge be comprehensively quantified using image analysis-based quantification methods.

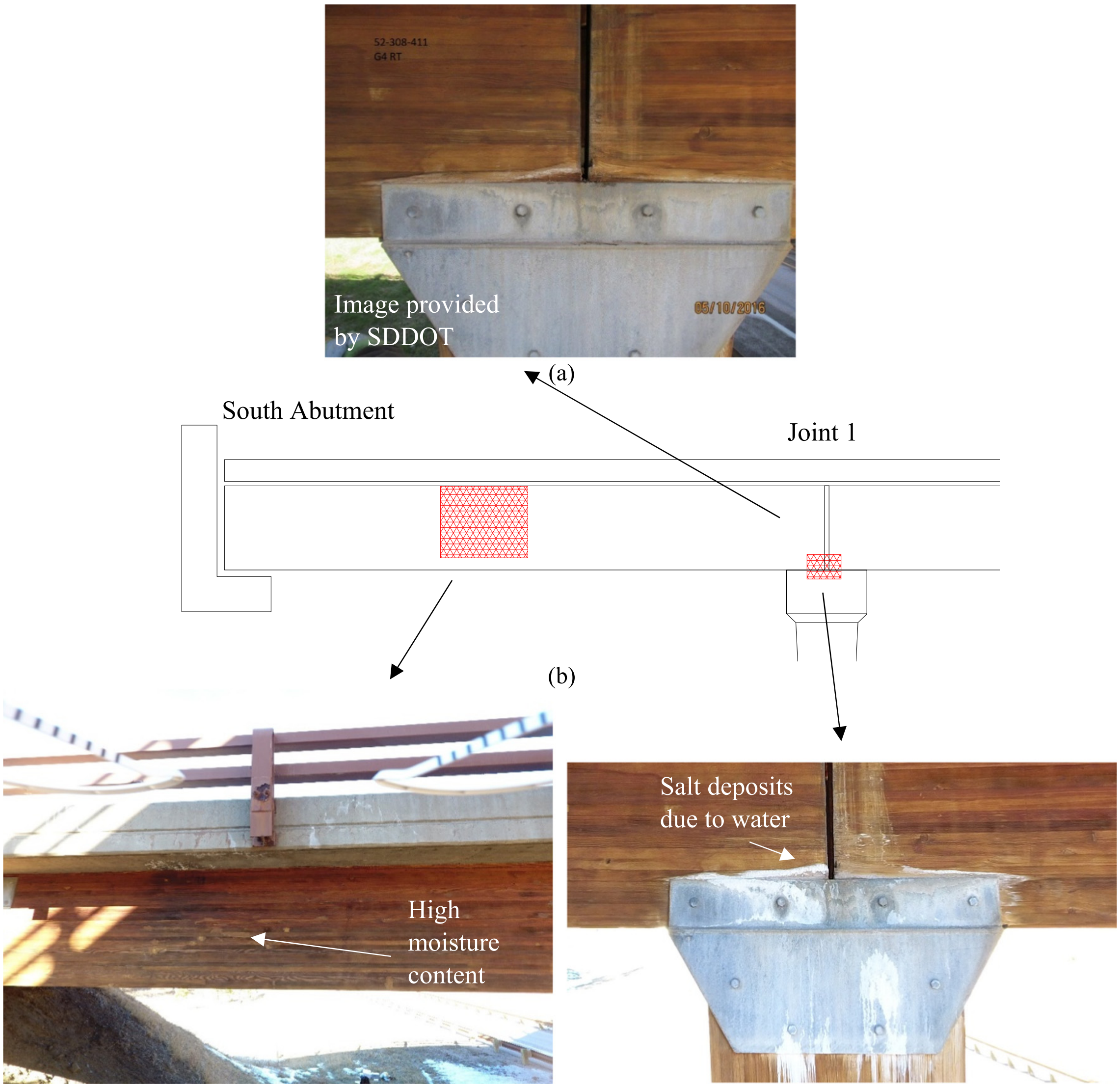


Fig. 14. Comparison of identified damage on girder: (a) image provided by SDDOT [20]; (b) damage location [20]; (c) damage on Girder 4 between South Abutment and Joint 1 (taken by Junwon Seo using drone); and (d) salt deposits due to water coming from deck at support of Girder 4 at Joint 1 (taken by Junwon Seo using drone).

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