Synthesis of Unmanned Aerial Vehicle Applications for Infrastructures

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Abstract: This paper is intended to provide the state-of-the-art and of-the-practice on visual inspection, monitoring, and analysis of infrastructure using unmanned aerial vehicles (UAVs). Several researchers have inspected various civil infrastructures, including bridges, buildings, and other structures, by capturing close-up images or recording videos, while operating UAVs. Various image analysis tools, such as the algorithm Morphological Link for Crack (Morpholink-C), were able to conduct precise measurements of crack thickness and length. Corrosion has also been detected using texture and color algorithms to investigate UAV-based images. Other analysis methods include structurally integrated sensors, such as digital image correlation equipment, which have helped to capture structural behaviors using UAVs. After the literature review was completed, a nationwide survey was distributed to Departments of Transportation (DOTs) to evaluate the current UAV-enabled inspection techniques that different DOTs have used or are planning to use for visual damage assessment for critical transportation infrastructures, especially bridges. Furthermore, a pertinent UAV selection was completed to indicate suitable UAVs for bridge inspection. Primary findings have shown that UAV-enabled infrastructure inspection techniques have been successfully developed to detect a broad variety of damage (including cracks and corrosions), and a few DOTs have used UAVs to inspect bridges as a more economical and versatile tool. **DOI:** 10.1061/(ASCE)CF.1943-5509.0001185. *© 2018 American Society of Civil Engineers.*

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Introduction

An unmanned aerial vehicle (UAV), referred to as a drone, is an aircraft without an aviator aboard. A drone has been commonly equipped with a camera capable of capturing high-resolution images and recording videos used to identify structural damage of infrastructures, among other uses (Eschmann et al. 2012; Nebiker et al. 2008). Drone technology has improved in recent years with an increasing number of researchers working to further develop its capabilities. Because of the efficiency and versatility of drone technology with evolving sensor technologies, this has become more appealing to inspectors of infrastructures.

There have been a number of studies on visual-based inspection of infrastructure for an efficient damage identification (Chan et al. 2015; Chen et al. 2011; Ellenberg et al. 2014; Hallermann and Morgenthal 2014; Henriques and Roque 2015; Irizarry and Bastos 2016; Khaloo et al. 2018; Lovelace and Zink 2015; Metni and Hamel 2007; Otero 2015; Rathinam et al. 2008; Roca et al. 2013; Wells and Lovelace 2017; Zhang and Elaksher 2012). For instance, Lovelace and Zink (2015) conducted the demonstration project to identify damage on different bridges in the state of Minnesota. Additionally, a study by Chan et al. (2015) identified an increase in bridge inspection and maintenance backlog as a result of current time-consuming and expensive inspection procedures. The researchers concluded that the drone-based inspection reduced the cost to approximately one-third and time significantly, as minimal large and heavy equipment needed to be transported and set up at the bridge site.

Further, analytical methods (including mathematical algorithms) have been used to study and quantify damage on different types of infrastructures (Aghaei et al. 2015; Bento et al. 2009; Chanda et al. 2014; Hutchinson and Chen 2010; Jahanshahi et al. 2009; Khaloo et al. 2018; Kim et al. 2017, 2015; McGuire et al. 2016). For example, Kim et al. (2015) developed an algorithm to determine crack thickness and length using images captured by a drone. The researchers determined that when using automated drones and visual imagery, the results were obtained in less time and with high precision. Use of the algorithm to quantify damage using data from drones could be a useful tool in alleviating the complications of direct field crack measurements, especially on inaccessible areas. In contrast, Jahanshahi et al. (2009) determined the crack length and thickness information using two methods: (1) morphological techniques to gather initial crack location information and (2) edge detection to obtain length, thickness, and inclination information of the crack. Additionally, the incorporation of color and texture algorithms were implemented to identify areas affected by corrosion.

In addition to visual and analytical methods, some researchers have investigated the implementation of incorporated sensors to analyze the infrastructure (Lee and Shinozuka 2006; Mascareñas et al. 2008; Reagan et al. 2017). For instance, Reagan et al. (2017) studied a drone with a three-dimensional (3D) digital image correlation (DIC) camera assembly to study long-term structural damage such as joint displacements. Use of the joint drone-3D DIC methodology allowed the measurement of damage on inaccessible areas more efficiently and in less time compared with conventional inspection techniques.

This paper is intended to summarize findings on current drone techniques to inspect and analyze different infrastructures,

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including bridges, buildings, and other structures. The emphasis of this literature review is to gather the Federal Aviation Administration (FAA) restriction issue to operate UAVs and the research efforts of different investigators on visual-based techniques, analytical algorithms, and incorporated sensors to inspect infrastructure. In addition to the literature review, this work will focus on a better understanding of the practices on drone technology in a critical transportation infrastructure (i.e., bridge) using an online-based survey. The survey, distributed to state Departments of Transportation (DOTs), was executed to collect practical information regarding their use of drones for bridge inspection. With the information gathered from the survey and literature review, this paper evaluated drone techniques used in past DOT research projects and capabilities of a variety of drones that have been used for different engineering purposes, in an attempt to recommend suitable drones for bridge inspection.

FAA Regulations for UAVs

Prior to 2016, the FAA regulations had several limitations for the commercial operation of drones (Lovelace and Zink 2015). One of the main limitations included the need for a Section 333 exemption certificate of authorization prior to any commercial drone operation, which was only given to pilots representing an organization (FAA 2016). After the newly implemented small UAV part 107 rule on June 2016, the limitations on the operation of UAVs were alleviated. Although the operation of the drones for business has become accessible to the public, the same core operational limitations still apply: (1) must use Class G airspace; (2) must keep the aircraft in sight (visual line-of-sight); (3) must fly under 400 feet; (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. A complete list of operational regulations provided by the FAA can be found in FAA (2016).

Visual Inspection of Infrastructures

A number of infrastructures across the United States need to be inspected to ensure appropriate serviceability and sufficient structural integrity. During recent years, many engineers, researchers, and DOTs have used drones to visually assess various infrastructures (Ellenberg et al. 2014; Moranduzzo and Melgani 2014). Damage on different types of infrastructures has been studied using drones. This section presents significant findings through an extensive literature review of studies made on visual-based techniques to inspect different types of infrastructures, including bridges, buildings, and others.

Bridges

Current visual bridge inspection methods with a crane and rope access are generally unsafe for inspectors because of the high elevation of bridges (Hachem et al. 1991; Koonce et al. 2011). In fact, most large-scale bridges span over water, making close visual inspection a difficult task. In the last decade, state DOTs and other federal organizations such as the United States Department of Agriculture–Forest Service (USDA–FS) began to investigate the capabilities of drones to visually assess bridges for potential damage as a more efficient alternative to current inspection practices (Barfuss et al. 2012; Dye Management Group 2014; Moller 2008; J. Seo, L. Duque, and J. Wacker, "[Bridge inspection protocol using drone technology]," submitted, Autom. Constr., ASCE, Reston, Virginia). Recently, Seo et al. (J. Seo, L. Duque, and J. Wacker, "[Bridge inspection protocol using drone technology]," submitted, Autom. Constr., ASCE, Reston, Virginia), inspected a timber bridge near the city of Keystone in South Dakota. The study evaluated the effectiveness of drones as bridge inspection tools for bridges with limited accessibility. During the field inspection, a recommended bridge inspection protocol to aid future generation bridge inspection was developed and applied to the bridge. The findings from Seo et al. (J. Seo, L. Duque, and J. Wacker, "[Bridge inspection protocol using drone technology]," submitted, Autom. Constr., ASCE, Reston, Virginia), in comparison to conventional inspection practices demonstrated the ability of the drone to effectively identify damage on the structure.

In 2008, Moller (2008), in a partnership with the California DOT (Caltrans), developed a twin-motor, single-duct, electric-powered drone designed to carry video cameras up to 61 m in elevation to enable close inspection of bridges and other elevated structures. The objective of Caltrans was to construct an "Aerobot" to easily access structural components at high altitudes, such as girders. They studied the use of cameras to closely examine bridge components as a new alternative at the time. The findings were acceptable, but some modifications needed to be made; the technology used by Moller (2008) followed more advanced instruments such as infrared, motion, and modeling sensors seen in recent research (Zhang and Elaksher 2012).

Other state DOTs, such as Florida and Minnesota DOTs, have investigated drone applications to inspect bridges in their states (Otero 2015). Specifically, Otero (2015) investigated different drones in terms of maneuverability, adaptability, software compatibility, payload, size, and user controls to perform bridge inspection. The efficiency of the selected drones, an Ardu Hexacopter (Ardu) and a Spider Quadcopter (Drone, FIT, Germany), was tested by investigating five different types of bridges. The drone's camera was to detect moderate crack thickness ranging from 0.51 to 2.03 mm. Additionally, a study of different types of bridges was conducted by Lovelace and Zink (2015) and Wells and Lovelace (2017). Lovelace and Zink (2015), working along with the Minnesota DOT (MnDOT), performed a demonstration project using an Aeyron Skyranger (Aeyron Labs, Waterloo, Canada) drone to inspect four bridges. During the inspection, damage such as corrosion and missing bolts based on imagery from the drone was observed. The selected bridges included a long, single-span prestressed concrete bridge, an open spandrel concrete arch bridge, a five-span steel underdeck truss bridge, and an arch truss bridge. At the end of the project, it was recommended that a suitable drone for inspection should have (1) an upward viewing camera and (2) the ability to fly without a global positioning system (GPS) signal. The Aeyron Skyranger used in the project was deemed not to be the most suitable drone to study a bridge. During Phase II, Well and Lovelace (2017) used a more advanced drone, the senseFly albris (Lausanne, Switzerland), which costs approximately $45,000 (in 2017). The SenseFly Albris was considered and compared later with other drones in the drone-selection section of this paper.

Buildings

Buildings, especially high-rise buildings, have been inspected using drones. Researchers have studied the possibility of using drones to identify damage on the structure (Ellenberg et al. 2014; Eschmann et al. 2012; Irizarry et al. 2012; Irizarry and Bastos 2016; Jizhou et al. 2004; Morgenthal and Hallermann 2014; Roca et al. 2013). For instance, Morgenthal and Hallermann (2014) used two Falcon drones, one for video and one for photos, to investigate a masonry church and detected critical cracks on a corner of the rooftop.

During this study, the pilot was able to approach the structure within 5 m to visually observe the damage and provide high-resolution images. Furthermore, Eschmann et al. (2012) developed strategies to visualize cracks on buildings. The drone selected for this task was an octocopter, which has a higher payload because of its eight rotors that elevate the platform. Different flight configurations were analyzed by the researchers, but it was determined that the best alternative was to fly horizontally across the building façade and then move to the next story. This flight pattern was determined by considering the needed speed and lens-induced effects (i.e., image distortion due to fish eye lens) for the postprocessing requirements of the images.

Other Structures

A variety of structures other than bridges and buildings, such as photovoltaic (PV) fields, dams, high mast luminaires (HML), dams, and industrial buildings have been inspected by drones. Such drones are equipped with different sensors and additional attachments, compared with the equipment that a drone uses for bridge or building inspection (Aghaei et al. 2015). For example, Aghaei et al. (2015) performed a thermographic assessment using a PLP610 Nimbus drone platform with a FLIR A35 infrared imaging sensor to identify defective panels. Because of the thermal characteristics of the panels, the defective panels are seen as hot spots on the infrared image. This methodology produces a faster inspection of the panels compared with manual visual assessment.

The inspection of HML was proposed by Otero (2015). Using a DJI Phantom 2 (Shenzhen, China) and a built in-house medium-sized drone, the Florida DOT and Florida Institute of Technology studied four different HMLs for damage or missing elements. Post-processing software was used to zoom in on the images and remove distortion as a result of the camera's lens curvature. The conclusions were satisfactory, and the drone effectively identified damage on the HML posts with great detail.

In addition, the study of industrial infrastructures, including industrial plans, chimneys and dams, was considered by Hallermann and Morgenthal (2013) and Henriques and Roque (2015). Henriques and Roque (2015) from the National Civil Engineering Laboratory in Lisbon, Portugal, investigated the use of drones for dam inspection. They used an Octocopter SKY II drone to better observe cracks on the dam's concrete surface. Previously, surveillance cameras and binoculars were used to observe the damage from the dam's base. Due to poor image quality, the methods were deemed to be ineffective. It was concluded that the drone, in addition to high-quality cameras, is considered an efficient mechanism to visually observe the dam due to its capability to obtain detailed images of critical sections located in inaccessible areas.

The industrial applications researched by Hallermann and Morgenthal (2013) consisted of a corrosion-level analysis for factors that commonly affect overall structural performance. They inspected a chimney 225 m high. The drone performed the inspection at different altitudes where known damage was located. They concluded that because of the high rise of the chimney, a drone would be safer and more efficient compared with a conventional inspection using expensive industrial climbers.

Visual Inspection–Based Analytical Methods

The use of directional sensors and computer software allows structural engineers to gather information beyond visual damage assessment alone. Computational algorithms have been studied to quantify damage such as crack thickness and length (Chanda et al. 2014; Ellenberg et al. 2014). Additionally, the use of laser scanners for 3D virtual modeling has been implemented to study different infrastructure, making drones an adaptable tool for inspection (Bento et al. 2009; Evaraerts 2008; Hallmark et al. 2001; Koch et al. 2014; Zhang and Elaksher 2012). This section presents findings on analytical methods applied to the inspection of different types of infrastructures.

Bridges

The development of autonomously flying drones coupled with damage detection algorithms has been of interest for different researchers (Metni and Hamel 2007; Michaelsen and Meidow 2014; J. Seo, L. Duque, and J. Wacker, "[Bridge inspection protocol using drone technology]," submitted, Autom. Constr., ASCE, Reston, Virginia, Seo et al. 2017a, b; Yin 2014). In detail, Metni and Hamel (2007) developed a control algorithm with orientation limits to guide an X4-Flyer drone. The concept is based on computer vision to navigate an unknown 3D environment and saturation functions to maintain the object in the camera's field of view. During the feasibility experiment, the drone was able to obtain high-quality data to be analyzed by inspectors. Additionally, with some image postprocessing treatment, cracks with a small thickness of 0.1 mm were observed. A different approach was used by Michaelsen and Meidow (2014). A structural pattern recognition system with an autonomously flying drone was used. The crack measurements were achieved with statistical analysis and sufficient data to cover a representative inspection area.

Moreover, the use of photogrammetric processing of images have aided researchers in creating 3D virtual models of bridges for their inspection (Khaloo et al. 2018). Khaloo et al. (2018), in partnership with the USDA–FS region 10, University of Alaska Fairbanks, and George Mason University, inspected an existing pedestrian timber truss bridge using a drone in Alaska. In detail, the researchers used a hexacopter drone named "Ptarmigan," built based on a DJI S800 airframe with gyrostabilized Sony Nex7 (Tokyo) and GoPro (San Mateo, California) cameras. The drone was able to identify damage on the bridge components (i.e., gaps between the end of kerf plate and sawn kerf in the brace). The 3D virtual model of the bridge in a dense 3D point cloud was created using the software PhotoScan, which was informed by the imagery data from the drone.

The ability to detect and measure concrete crack thickness and length using drones has been widely researched (Chanda et al. 2014; Chen et al. 2011; L. Duque, J. Seo, and J. Wacker, "[Bridge damage quantification methodology using UAV platform]," submitted, J. Br. Eng., ASCE, Reston, Virginia; Duque 2017; Ellenberg et al. 2016; Eschmann et al. 2013; Jahanshahi et al. 2009; Kim et al. 2015). Duque et al. (L. Duque, J. Seo, and J. Wacker, "[Bridge damage quantification methodology using UAV platform]," submitted, J. Br. Eng., ASCE, Reston, Virginia), developed a drone image–based bridge damage quantification protocol. The protocol included image-quality assessment techniques using image-quality parameters such as sharpness and entropy in addition to damage quantification methods including pixel-based and photogrammetric-based measurements. Furthermore, Duque et al. (L. Duque, J. Seo, and J. Wacker, "[Bridge damage quantification methodology using UAV platform]," submitted, J. Br. Eng., ASCE, Reston, Virginia), applied the proposed protocol to a timber arch bridge and were able to measure crack length and thickness and rust staining on the structure. Moreover, Kim et al. (2015) used the specially designed Morphological Link for Crack (Morpholink-C) algorithm and were able to measure the crack thickness of 0.1 mm and greater. Additionally, Ellenberg et al. (2016) from the University of Drexel, Philadelphia, studied the effectiveness of drones to detect cracks in terms of the distance to the structure. The conclusions from the study demonstrated that with a high-resolution camera it is possible to detect a crack thickness of 0.75 mm at a distance of 3 m.

A critical challenge with drone-enabled damage identification and measurement is the image sharpness or clarity. Researchers have studied the effects of environmental conditions (e.g., wind) (Hallermann and Morgenthal 2014; Morgenthal and Hallermann 2014). Morgenthal and Hallermann (2014) used a computer vision–based crack detection algorithm to compare the accuracy of crack measurements from blurry and clear images. To solve this problem, a probability of detection was generated from different parameters (i.e., drone properties and wind) and then the parameters were reorganized to obtain the desired image quality.

Other research efforts to investigate bridge inspection results during windy conditions have been made by Guerrero and Bestaoui (2013). Guerrero and Bestaoui (2013) used three different approaches: (1) Zermelo-Traveling Salesman Problem (TSP), (2) Meshing techniques with Zermelo-TSP, and (3) Zermelo-Vehicle Routing Problem (VRP). Zermelo-TSP computed the most effective route the drone can take to inspect the structure. The meshing techniques combined with the Zermelo-TSP method created interest points along the structure using a meshing algorithm, and then the Zermelo-TSP determined the most time efficient order to inspect all of the points. Finally, the Zermelo-VRP works similarly to the Zermelo-TSP method, but it considers the energy limitations of the drone.

Buildings

Buildings have been reconstructed in 3D virtual models using computer programs to identify damage (Daftry et al. 2015; Ellenberg et al. 2014; Jizhou et al. 2004; Püschel et al. 2008; Roca et al. 2013; Zhang et al. 2011; Zischinsky et al. 2000). Using drones and terrestrial images, Püschel et al. (2008) reconstructed Castle Landenberg using photogrammetric processing of images. To create the 3D virtual model, the use of photomodeler software helped the researchers to recreate the structure in detail. Other equipment, such as high-resolution directional sensors or laser sensors, have also been used. The accuracy of 3D virtual models relies on the quality of the gathered images. The greater the image pixel count, the more detail can be observed to inspect buildings. In some cases, a high-resolution images are not required. For example, when only general façade dimensions are desired, a laser sensor could be more suitable in terms of cost. Roca et al. (2013) from the University of Vigo, Spain, performed an analysis using a low-cost drone with a Microsoft Kinect (Redmond, Washington) sensor to compare it with a laser scanner in terms of image quality. They concluded that the model obtained with the Microsoft Kinect was of good quality and the results were comparable to those of a laser scanner.

The generation of 3D virtual models of buildings can also provide the engineer with supplementary information of critical roof section, severe weather building exposure, and general location of structural components (Eschmann et al. 2013). In fact, Eschmann et al. (2013) from the Fraunhofer Institute for Non-Destructive Testing investigated the use of drones for building inspection and monitoring. Using an octocopter with a high-resolution camera, the researchers inspected a building for damage. The process was based on taking digital images at close intervals to recreate the structure with the help of a photogrammetry computer program. Because of the size of the building, a visual inspection from a 2D virtual model was ideal, and the virtual image was separated into several small sections for ease of damage observation.

Additionally, crack detection can be complicated in buildings, especially in light-colored ones, but with the help of an image processing software, Eschmann et al. (2013) enhanced the color of the crack using two methods: (1) adding additional color value and (2) edge detection. The additional color value analyzes the image and determines whether the individual pixels need either more black or more white to produce black crack areas. In contrast, the edge-detection methodology searches for a sudden change in color, commonly seen in cracks.

Other Infrastructures

Analytical methods have been applied to other structures such as pipelines and highways (Rathinam et al. 2008). The study performed by Rathinam et al. (2008) was based on a directional logarithm inputted into the single-wing Sig Rascal (SIGPlanes.com, Montezuma, Iowa) drone. To demonstrate the feasibility of this inspection, they performed a study of a 700-m-long canal and demonstrated that the drone can autonomously follow the canal path. Some of the benefits include the rapid inspection and monitoring of important pipelines, such as the Alaska oil pipeline system, where a shutdown could cost about $1 million per hour (in 2008). Additional benefits of the study include a reduced cost to inspect structures with large distances and the ability to perform the monitoring process faster than a human visual inspection.

Further studies (Remondino et al. 2012; Siebert and Teizer 2014; Turner et al. 2012) also suggest the use of drones for inspection of construction zones as conducted by Rathinam et al. (2008). For instance, Siebert and Teizer (2014) investigated the use of drones to perform surveying-related work. The drone, a customized Mikrokopter Quad XL (HiSystems GMBH, Moormerland, Germany), was able to produce a 3D model of construction zones and determine places along the road where fills and cuts were needed to level the surface. They calculated the volume of fills and areas to be covered using Agisoft professional PhotoScan software. A similar approach was followed and performed by Remondino et al. (2012) using a microdrone called MD4-200 (Microdrones, Siegen, Germany) for mapping extensive zones. Turner et al. (2012) also used a similar approach by generating a point cloud using an automated drone, to investigate extensive areas.

Additional structures such as dams have been reconstructed in a 3D virtual environment. The 3D virtual model was generated from images using the software VisualSFM (structure from motion) to inspect the dam surface (Henriques and Roque 2015). In depth, Henriques and Roque (2015) used the software eCognition (from Trimble) to identify relevant characteristics, including deposits of calcium carbonate due to water leakages, reddish calcium carbonate deposits, and wet concrete. The researchers concluded that the drone, accompanied with high-quality cameras, was an effective tool to inspect dams because they could obtain close-up images of critical sections or inaccessible areas of the dams.

Finally, other structures investigated using analytical methods include industrial plants and PV fields (Aghaei et al. 2015; Bento et al. 2009; Moranduzzo and Melgani 2014; Tyutyundzhiev et al. 2015). Both Bento et al. (2009) and Moranduzzo and Melgani (2014) investigated corrosion detection. Moranduzzo and Melgani (2014) developed a method that consisted of taking two pictures at two different times and then using a three-step process to (1) align the images, (2) identify damages using a threshold technique, and (3) compare and determine the corrosion size. Aghaei et al. (2015) used binary images to locate the defective solar panels. The images were obtained using a grayscale and a Gaussian filter to detect the defective panels. A more in-depth study of PV fields inspection was conducted by Tyutyundzhiev et al. (2015). Methods such as image and aerial photo-mapping techniques were considered. Additionally, different low-cost camera models (e.g., Canon IXUS 135 IS, Tokyo) were used to gather aerial images and video. It was concluded that the drone was capable of helping to reproduce 3D virtual models and that the integrated technology was able to conduct PV inspection.

Infrastructure Inspection with Integrated Sensors

Few researchers have investigated the use of drones to analyze different aspects of infrastructure such as deflection of bridges (Lee and Shinozuka 2006; Mascareñas et al. 2008). This technology can aid structural engineers in performing different nondestructive tests such as joint deflection. Although Lee and Shinozuka (2006) did not use a drone for their analysis, the use of a visual approach to determine deflections could potentially be incorporated into drones in the future. The method they conducted used image-processing techniques to obtain deflection in real time. Several innovative features, including a high-resolution dynamic measurement, remote sensing, cost-effectiveness, real-time measurement and visualization, ease of installation and operation, and no electromagnetic interferences are implemented to measure the bridge displacement. The deflection is calculated using a sensor located at the desired plane (i.e., girder midspan) and a video camera shooting at the sensor to gather the measurements. With the use of a target recognition algorithm, the number of pixels displaced by the bridge due to external forces can be determined. The researchers concluded that the method can be implemented with a high level of accuracy and will be cost-effective and easy to use.

Additionally, Mascareñas et al. (2008) inspected a bridge using integrated sensors. They used an X-Cell Spectra G drone to transmit microwave energy to a wireless sensor node located at the structure. After the node is charged the drone can receive displacement measurements to be analyzed. During this experiment, the researchers' main goal was to charge the node, and a further study will be performed to obtain actual measurements from piezoelectric sensors located at the bridge. The innovative approach used can aid in structural health monitoring (SHM) applications to assess structures after a natural disaster occurs.

Further, the use of DIC cameras integrated with drone technology has aided researchers in monitoring long-term deflections (Reagan et al. 2017). Reagan et al. (2017) studied the enhancement of the drone's capabilities by introducing an innovative drone-3D DIC platform for long-term SHM. It was proven that the platform was able to accurately measure the evolution of displacements at a deck joint due to aging. They concluded that the new drone-3D DIC platform can produce more accurate results and better performance when compared with visual inspection techniques.

UAV Selection

After completing the literature review of drone techniques to inspect, monitor and analyze infrastructures, a drone for infrastructure inspection was recommended. While performing the literature review, several researchers investigated different drones to compare their capabilities in terms of data acquisition. The goal of this paper was to provide a comprehensive summary of drone inspection techniques and pertinent image data investigation tools and relate them to the most suitable drone for infrastructure inspection. Based on the knowledge from the literature review, the following considerations needed to be verified when reasonably selecting the most suitable inspection drone:

1. Flying time over 20 min: A relatively long flying time is beneficial for a more efficient structure inspection by limiting the need for additional batteries and allowing for longer inspection times;
2. Additional camera on top of drone: A second camera facing straight up to inspect underneath the bridge will allow for its comprehensive inspection;
3. Camera resolution with low illumination: Low illumination reduces the image quality, as small damage would be challenging to detect. Additional flashlights can be attached to a drone to enhance illumination;
4. Video resolution: High-resolution video is required to visually observe details of damage;
5. Payload capacity: It would be beneficial for potential attachments that might be required to be carried by a drone;
6. Drone lights: Light-emitting Diode (LED) lights attached to a drone will provide some extra illumination required for efficient damage observation underneath a bridge; and
7. Remote range: Some structures might not be relatively close from the pilot location. Long-range modules for remote control will allow for inspection of a structure at long distances.

With the required seven considerations, 13 drones with a variety of prices, physical sizes, and manufacturers were identified and listed in Table 1. The drones and each of their capabilities were compared in terms of the aforementioned considerations and rated from 1 (not suitable) to 5 (extremely suitable). From the table, the most appropriate drone is the senseFly albris, rated "5," because of its (1) ability to rotate the camera vertically 180° with an integrated flashlight, infrared camera, and wide-angle camera; (2) different flight modes (e.g., GPS-Mapping and manual) to allow the drone to program missions or fly under bridges where GPS signal is unavailable (many researchers have expressed issues with the low signal of the drones); and (3) effectiveness for bridge inspection, which was previously demonstrated through the MnDOT project. However, the elevated cost of the drone, close to $45,000, may not be suitable for many inspectors.

Alternatively, options such as the DJI Matrice 100, DJI S900, DJI Phantom 3 Pro, and DJI Phantom 4 were deemed to be suitable at a more affordable price compared with the senseFly albris. The DJI Phantom 4 was selected over the others because of its performance and versatility in meeting the aforementioned specifications at a reasonable cost. Additional equipment, such as the obstacle avoidance technology, of the drone will be beneficial while approaching a structure to prevent damage to both structure and drone components. Another key consideration is the ability to fly without GPS signal. This enables the drone to inspect underneath bridges without the problem of losing satellite connection, as stated previously. Some attachments including a flashlight and second camera could be added to the drone to overcome such inspection challenges.

Survey

An online survey sent to all 50 DOTs was also conducted to gather additional hands-on information about the use of drones for infrastructure inspection, especially bridge inspection. Nineteen responses to the online survey were received from different DOTs: Idaho, Iowa, Illinois, Missouri, Wyoming, Florida, Delaware, New York, Wisconsin (2), Alaska, Arkansas, Nevada, South Dakota (2), Kentucky, Arizona, and Colorado, in addition to Alaska USDA–FS. It was specified that seven states, including Florida, Iowa, Idaho, Kentucky, New York, Wisconsin and Alaska, have used or planned to use drones for bridge inspection. This shows the increasing interest among states to use the drone technology. The summary of the responses for the survey are presented subsequently.

Table 1. Comparison of identified drone specifications

Drone	Price	Approximate fly time	Upward camera view	Camera resolution with low illumination	Video resolution	Payload capacity	Other source of light	Remote range	Satisfactory[a]
(a) DJI Inspire 1 (DJI 2014a)	$2,000	18 min	94° vertical range	Optional flashlight attachment will improve quality	4k/1080p	1,700 g	Drone has red LED lights	2,000 m	3
(b) Voyager 3 (Walkera 2015)	$2,000	25 min	Facing upward at an angle	Optional flashlight attachment will improve quality	1080p	320 g	Drone has red and blue LED lights	1,000 m	2
(c) DJI Matrice 100 (DJI 2013a)	$2,800 – $3,300 + $750 for camera	40 min	Need to buy camera	Optional flashlight attachment will improve quality	1080p	1,000 g	Drone has green LED lights	5,000 m	4
(d) DJI Phantom 3 pro (DJI 2013b)	$1,200 + $499 for GoPro camera	23 min	94° vertical range[b]	Optional flashlight attachment will improve quality	4k/1080p	462 g	Drone has red and yellow LED lights	5,000 m	4
(e) DJI Phantom 4 (DJI 2016)	$1,800 + $499 for GoPro camera	28 min	94° vertical range[b]	Optional flashlight attachment will improve quality	4k/1080p	462 g	Drone has red and yellow LED lights	5,000 m	4
(f) Yuneec Typhoon H (Yuneec 2016)	$1,600	25 min	Facing upward at an angle	Optional flashlight attachment will improve quality	4k/1080p	600 g	Drone has green, red, and blue LED lights	1,000 m	3
(g) DJI S900 airframe (DJI 2014b)	$3,000 + $750 – $1,300 for camera	20 min	Optional attachment	Optional flashlight attachment will improve quality	4k/1080p	4,300 g	No LED lights	1,000 m	4
(h) Yuneec Typhoon 4K (Yuneec 2015)	$1,100	25 min	115° vertical range	Optional flashlight attachment will improve quality	1080p	600 g	Drone has red and yellow LED lights	800 m	3
(i) Blade Chroma (Horizon Hobby 2015)	$700	30 min	Facing upward at an angle	Optional flashlight attachment will improve quality	4k/1080p	200 g	Drone has green, red, and blue LED lights	400 m	2
(j) Autel robotics X-star premium (Autel Robotics 2016)	$900	25 min	108° vertical range	Optional flashlight attachment will improve quality	4k/1080p	180 g	No LED lights	2,000 m	2
(k) SenseFly eBee (Sensefly 2016a)	$25,000	50 min	No	Optional flashlight attachment will improve quality	1080p	—	No LED lights	3,000 m	1
(l) SenseFly albris (Sensefly 2016b)	$45,000	22 min	Yes	Flashlight included	4K/1080p	—	Drone has green, red, and blue LED lights	2,000 m	5
(m) Topcon Sirius Pro (Top Con 2016)	$53,000	55 min	No	Optional flashlight attachment will improve quality	1080p	—	No LED lights	3,000 m	1

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

Question 1 of the survey enquired about whether the state has used or is planning to use any drone for bridge inspection. In addition, if they have used or are planning to use drones, it enquired about which drone was used, including attachments. Only one state (Alaska USDA–FS), of those that answered Question 1, had used a drone for bridge inspection. The remaining six state DOTs were planning to perform bridge inspection using drones in the near future. A summary of the responses is presented in Table 2.

For Question 2, material regarding drone techniques for bridge inspection was requested from the DOTs. The question asked, "What techniques or data were or will be used to inspect bridges?" All of the DOTs that participated in the survey by responding to the first two questions mentioned that images and video are the most relevant information used to detect damage. Fig. 1 shows the relevant data. Eight state DOTs stated that imagery and video data are considered the most effective in identifying damage on bridges. Among the eight DOTs, five of them, including Wisconsin (2), Colorado (1), Idaho (1) and Iowa (1), specified that data obtained from thermal cameras are the second most important source for damage detection. Finally, the response from the Colorado DOT stated that displacement sensors provide the critical data necessary for the damage identification. Alaska USDA–FS responded that 3D site reconstruction photogrammetric software [e.g., structure from motion (SfM)] is important for detailed damage investigation.

Question 3 enquired about the most necessary data and challenges that drone technology may have for bridge inspection. Numerous challenges were specified by several state DOTs regarding the technology, because of its relatively new appearance on the market, especially for bridge inspection. Details about the answers to Question 3 are listed in Table 3.

Question 4 asked the DOTs for details about their main concerns when inspecting bridges using drones. Safety and regulation concerns were specified by several state DOTs, because of the relatively new appearance of the drone technology, especially for bridge inspection. Some states such as Delaware, Florida, Idaho, Illinois, Iowa, South Dakota, Wisconsin, and Wyoming expressed that regulations are the biggest challenge. Other states including Alaska expressed that low-light conditions, upward viewing

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Table 2. Summary of responses for Question 1 of survey

	Question		
State	Has your state used or is your state planning to use any drone for bridge inspection?	Specify your drone type	Specify attachments
Alaska DOT	No	—	—
Alaska USDA–FS	Yes, have used	Purpose-built hexacopter (based on DJI S800 airframe)	Gyro-stabilized Sony Nex7 and GoPro unit
Arizona DOT	No	—	—
Arkansas DOT	No	—	—
Colorado DOT	No	—	—
Delaware DOT	No	—	—
Florida DOT	Yes, planning to use	Not specified	—
Idaho DOT	Yes, planning to use	Coaxial octocopter	—
Illinois DOT	No	—	—
Iowa DOT	Yes, planning to use	Aibotix X6	—
Kentucky DOT	Yes, planning to use	Rotor UAV	GoPro camera
Missouri DOT	No	—	—
Nevada DOT	No	—	—
New York DOT	Yes, planning to use	Not specified	—
South Dakota DOT	No	—	—
Wisconsin DOT	Yes, planning to use	Not specified	—
Wyoming DOT	No	—	—

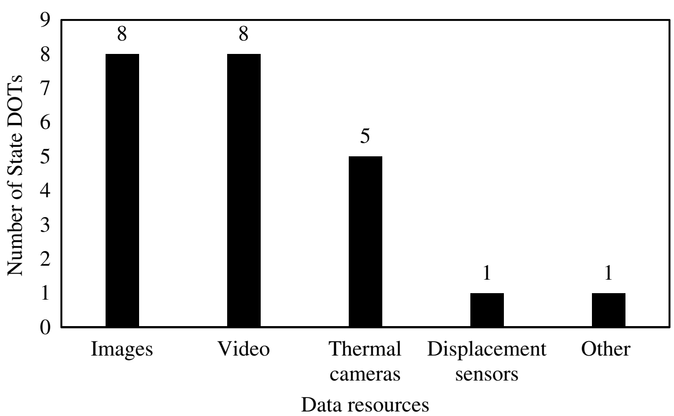

Fig. 1. Responses to Question 2 of survey.

cameras, and GPS signal could be a challenge, especially during underside inspection of decks. Finally, a concern regarding traffic safety was expressed by Arkansas, Colorado, Illinois, Kentucky, and South Dakota.

Question 5 requested information from DOTs about either their past or ongoing research projects involving UAV inspection techniques. Several state DOTs, including Arkansas, Arizona, Illinois, Missouri, Wyoming, Delaware and New York, did not have any ongoing research. The remaining state DOTs provided specifics about their ongoing research. For example, the Alaska USDA–FS specified a demonstration project conducted in 2015 to evaluate the capabilities and limitations of the aerial platform. This study was conducted by Khaloo et al. (2018) and was presented in this literature review. Other studies such as the proof of concept study by the Florida DOT led by Otero (2015) is summarized in this paper. Other states with ongoing research include Colorado, Idaho, Iowa, Kentucky, Nevada, and Wisconsin.

Finally, Question 6 requested information regarding future research plans that are relevant to drone techniques in inspecting bridges. Once more, the state DOTs from Question 5, with the addition of South Dakota and Alaska, did not mention any future research plans involving drone techniques. The remaining states including Wisconsin, Kentucky, Iowa, Florida, and Alaska USDA–FS expressed their intention to evaluate the effectiveness of drones through field studies to determine their applicability for bridge inspection.

The survey results were somewhat as expected, with few state DOTs having ongoing research using drones and therefore being very skeptical about this new technology. It was confirmed that the most common data necessary for bridge inspection are images and videos. Nevertheless, several state DOTs mentioned concerns regarding safety, traffic control, privacy, frequent changes in FAA regulations, and others. Hence, these and other concerns should be considered when inspecting infrastructure in the future.

Summary and Conclusions

Different methods were presented in this state-of-the-art and of-the-practice on drone techniques to inspect, monitor, and analyze infrastructure. The procedures were analyzed according to three different categories [(1) visual-based techniques, (2) analytical techniques, and (3) incorporated structural sensors] to examine infrastructure. Based on the findings from this literature review, drone selection, and survey, the following conclusions, limitations, and recommendations can be made to improve the use of drones as infrastructure inspection tools:

1. Visual inspection of infrastructure has been used during the past decade by different DOTs and engineers. Bridges, buildings, and other structures such as concrete dams and industrial plants have been studied. The results from recent findings are satisfactory and have led engineers to visually inspect structures more efficiently and in less time compared with conventional inspection techniques. Additionally, images obtained from such studies have been used to detect cracks, corrosion, and other damages. In addition, the results obtained from the drone-enabled inspections have similar or better image quality compared with traditional inspection methodologies. One of the benefits identified by some researchers is the ability to access bridge areas with restricted accessibility for inspectors, allowing a more comprehensive infrastructure inspection;

Table 3. Summary of responses for Question 3 of survey

State	Question	
	Necessary data	Inspection challenges
Alaska DOT	—	—
Alaska USDA–FS	High-definition imagery along with a replicable inspection pattern/process	Weather/wind, payload limitations, battery life, safe stand-off distances and collision avoidance, and lighting conditions for under-bridge viewing
Arizona DOT	—	—
Arkansas DOT	—	—
Colorado DOT	—	—
Delaware DOT	—	—
Florida DOT	Images are the most important; data from video and thermal cameras may be important; displacement sensors are probably only useful in rare instances	—
Idaho DOT	—	Issues related to the platform, autonomous control of UAVs, postprocessing of acquired data
Illinois DOT	—	—
Iowa DOT	High-quality images are necessary	Regulations are the biggest challenge
Kentucky DOT	Video data would be most necessary	Loss of signal underneath a bridge
Missouri DOT	—	—
Nevada DOT	—	—
New York DOT	—	—
South Dakota DOT	—	—
Wisconsin DOT	Data will be used to quantify condition and change in condition	FAA rules are the biggest obstacle
Wyoming DOT	—	—

2. Integrated analytical methods have aided visual inspection to detect damage, program flights, and create 3D virtual models. Some of the most relevant features include autonomous flights, crack thickness and length measurement, and corrosion growth analysis. The literature review indicated the versatility of drones to detect damage on different structures and materials. Attachments such as multisensors, infrared cameras, and laser sensors helped to generate different types of images for inspection purposes. Some computer software have been developed to measure crack thickness and length, corrosion, and to create 3D virtual models using photogrammetric processing of images;
3. Integrated structural sensors have not been studied widely; this technique is proposed to be researched further because of the benefits in structural health monitoring and structural analysis. Current methods are limited in equipment and implementation, as presented in this review. An innovative method to measure deflection using digital image correlation cameras integrated with drones to measure long-term deflections was presented as a promising technique to inspect infrastructure with limited accessibility. This method of integrated DIC cameras and drone technology could potentially be further developed to study crack propagation and the monitoring of other types of damage such as joint displacement; and
4. The results from the survey to state DOTs demonstrated the interest of these organizations to conduct research projects on drone technology. Currently, there is only one state among those who participated in the survey that has conducted bridge inspection using drone. Florida, Iowa, Idaho, Kentucky, New York, and Wisconsin are planning to use drones in the near future, which shows the increasing interest for this new technology.

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