Transportation Research Record

UTILIZING UAS AND REALITY MODELING TO IMPROVE BRIDGE INSPECTION RESULTS

--Manuscript Draft--

Full Title:	UTILIZING UAS AND REALITY MODELING TO IMPROVE BRIDGE INSPECTION RESULTS
Abstract:	Bridges are a key part of our transportation system and maintaining this infrastructure is important to ensure the safety of the traveling public and to effectively manage these valuable assets. Safety inspections not only ensure the structural integrity of a bridge but provide valuable data to decision makers. The Minnesota Department of Transportation and Collins Engineers, Inc. has completed this third phase of research focused on utilizing drones as a tool for improving the quality of bridge inspections. The previous phases focused on the rules and regulations, drone hardware and the ability of drones to collect quality inspection data. This phase of research has identified new drone technology and methods to address limitations identified in Phase II. More importantly, this research phase has focused on the value of data collected during the inspection and finding ways to process the data into actionable inspection deliverables that greatly improve the quality of the inspections. These inspection deliverables better communicate the inspection results to bridge owners and engineers. Our world is being transformed by technology including drones that can collect, process, store, and analyze large amounts of data and this research is applying the same transformative concepts and technology to improve bridge inspection outcomes.
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ABSTRACT

Bridges are a key part of our transportation system and maintaining this infrastructure is important to ensure the safety of the traveling public and to effectively manage these valuable assets. Safety inspections not only ensure the structural integrity of a bridge but provide valuable data to decision makers. The Minnesota Department of Transportation and Collins Engineers, Inc. has completed this third phase of research focused on utilizing drones as a tool for improving the quality of bridge inspections. The previous phases focused on the rules and regulations, drone hardware and the ability of drones to collect quality inspection data. This phase of research has identified new drone technology and methods to address limitations identified in Phase II. More importantly, this research phase has focused on the value of data collected during the inspection and finding ways to process the data into actionable inspection deliverables that greatly improve the quality of the inspections. These inspection deliverables better communicate the inspection results to bridge owners and engineers. Our world is being transformed by technology including drones that can collect, process, store, and analyze large amounts of data and this research is applying the same transformative concepts and technology to improve bridge inspection outcomes.

Keywords: Bridge, Inspection, Drone, UAS, Reality Capture, Asset Management, Big data.

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EXECUTIVE SUMMARY

The ability to collect and utilize large amounts of data is transforming our world. Many industries including healthcare, finance, energy, communication and transportation are finding ways to utilize data to improve people's lives. The Minnesota Department of Transportation (MnDOT) and Collins Engineers, Inc. are utilizing drones to collect and process large amounts of data during bridge inspections with the goal of improving the quality of bridge inspections and improving safety for both inspectors and the traveling public. Processing software and inspection specific asset management platforms are giving bridge engineers the ability to utilize this data to improve the quality of bridge inspections and accelerating their ability to effectively manage these important assets.

The Federal Highway Administration (FHWA) has identified this technology as a tool that can provide benefits for bridge inspections and the transportation industry. In the hands of qualified and experienced bridge inspectors, drones have the ability to improve the safety and quality of inspections. One of the key contributing factors to the success of the National Bridge Inspection Program is the ability to collect quality data on the nation's bridges which can be analyzed to ensure quality inspection results. Drones are a platform for collecting quality data, and the use of this technology satisfies one of the primary goals of the NBIS. As the FHWA moves towards risk-based inspections, drones are playing an important role as a tool for an experienced and qualified bridge inspector.

Inspection specific drone technology is maturing and several drone models now exist that serve the inspection and asset management industry. These drones include features important to bridge inspection such as sense and avoid, infrared imaging, autonomous flights, and collision-tolerant features. Inspection specific drone models have their own strengths and weaknesses, but all can accomplish the task of obtaining high-quality data. Collision tolerant drones are one type of inspection specific drone which enables inspectors to reach areas previously inaccessible by drone. As technology has improved, the focus has shifted from the ability to collect data to making effective use of the data.

Safety of bridge inspectors and the traveling public during bridge inspections is critical. A risk often associated with bridge inspection is the failure of access equipment including UBIV's. Perhaps the highest risk factor associated with bridge inspection is the closure of traffic lanes. The risk of injury or death is for both the traveling public and bridge inspectors. While statistics on injuries and fatalities are difficult to find, news article searches show fatalities happen every year. For many bridge inspections, the use of UAS can eliminate or reduce the need for access vehicles and/or lane closures thereby reducing risk.

This research phase implemented UAS technology on 39 bridges including a wide range of bridge sizes, types, and locations. The results of this research effort demonstrated that drone technology and processing software are effective tools to improve the quality of bridge inspections in addition to improving safety and reducing costs. Traditional access and reporting methods will continue to be utilized even as UAS technology improves, but UAS has proven to

Under Review

be another effective tool. This report will help bridge owners identify opportunities to improve the quality of their inspections, improve safety, and reduce costs.

Under Review

TABLE OF CONTENTS

CHAPTER 1: Introduction 7

1.1 Project Background and Objectives 7

CHAPTER 2: UAS Hardware 9

2.1 Inspection-Specific Commercial UAS 9

2.1.1 Mapping and Photogrammetry UAS 9

2.1.1.1 Commercial Inspection Specific Drones 12

2.1.1.2 Collision Tolerant UAS 12

2.2 Opportunities for Hardware Advancement 15

CHAPTER 3: Data Processing and Deliverables 16

3.1 Data Processing 16

3.1.1 Processing Inputs 16

3.1.1.1 UAS Images 16

3.1.1.2 Terrestrial Photography 17

3.1.1.3 Ground Control and Scaling 18

3.1.2 UAS Reality Modeling Platforms 19

3.1.3 Deliverables 20

3.1.3.1 Models and Photologs 20

3.1.3.2 Orthomosiac and Orthoplanes 21

3.1.3.3 Cloud Sharing 22

CHAPTER 4: Cost Analysis 23

CHAPTER 5: Safety Improvements 24

CHAPTER 6: Conclusions and Recommendations 26

6.1 Conclusions 26

6.1.1 Cost 26

6.1.2 Improved Deliverables/Reality Modeling 26

6.1.3 Collision Tolerant/Confined Spaces 26

Under Review

6.1.4 Safety 27

6.2 Recommendations 27

AUTHOR CONTRIBUTION STATEMENT ……..27

REFERENCES..... 28

LIST OF FIGURES

Figure 2.1 senseFly Emotion Software Flight Controls..... 10

Figure 2.2 Image of the senseFly albris UAS. 11

Figure 2.3 Example of albris High-Resolution Image Capability. 12

Figure 2.4 Photograph of the Elios UAS Rolling Inside a Steel Box Beam..... 14

Figure 3.1 3D Model of Bridge Pier Created From Terrestrial Photos 18

Figure 3.2 AeroPoint Automated Ground Control Point Figure..... 19

Figure 3.3 Pix4D 3D Reality Model Photo Log ……...20

Figure 3.4 Pix4D 3D Triangular Mesh 21

Figure 3.5 Orthomosaic of Bridge Site 21

Figure 3.6 Pix4D Bridge Facade Orthoplane..... 22

Figure 3.7 Cloud Virtual Inspector 22

APPENDIX A Cost Comparisons Between Traditional Inspection and UAS…….....24

Under Review

CHAPTER 1 INTRODUCTION

1.1 Project Background and Objectives

Bridges are a key part of our transportation system, and maintaining this infrastructure is important to ensure the safety of the traveling public and to protect these valuable assets. The most important objective during a bridge safety inspection is to verify the structural integrity of the bridge. Information gathered during bridge inspections is also used to give bridge owners and engineer's data to plan for the maintenance, rehabilitation and replacement of bridges. The National Bridge Inspection Standards (NBIS) set minimum requirements for bridge inspections including inspector qualifications, inspection intervals and inspection procedures. The NBIS was implemented into Federal law in 1968, and bridge inspections have been documented in a similar manner until recently. Recent technological advancements in Unmanned Aerial Systems (UAS) hardware and software have demonstrated that this transformative technology can also improve upon the quality of bridge inspection. Inspection specific drones have proven effective in providing high quality data that can be processed by software into multiple formats that can easily be shared via the Cloud.

In the summer of 2015 and 2016, two research phases were carried out to evaluate the use of UASs for bridge inspections by the MnDOT Bridge Office. The resulting studies were published by MnDOT's Research Services. As this research has progressed, the focus has shifted from data collection to data analysis and presentation.

An Unmanned Aircraft System (UAS) is defined by the Federal Aviation Administration (FAA) as an aircraft operated without the possibility of direct human intervention from within the aircraft. UASs are commonly referred to as drones, and the names can be used interchangeably. Inspection specific UAS technology is maturing, and several models now exist that serve the inspection and asset management industry. These drones include features important to bridge inspection such as sense and avoid, infrared imaging, autonomous flights, and collision-tolerant features. Each have their own strengths and weaknesses but can all accomplish the task of obtaining high-quality data. As the technology improved, the focus shifted from UAS hardware to data.

An opportunity identified during previous MnDOT research, was the ability to inspect very tight areas and confined spaces. One focus of this research phase was identifying a drone that could accomplish this challenging task. Another research objective was to scale the UAS inspection effort to demonstrate that full implementation is achievable. This research phase implemented UAS technology on 39 bridges including a wide range of bridge sizes, types, and locations to demonstrate the benefits and challenges of employing UAS on a large scale. When processed with modeling software, high-quality images can be collected and processed into useful inspection data such as point clouds, 3D photologs, and orthoplane images.

The ability to efficiently utilize large amounts of data is transforming our world. Drones can collect large amounts of data during bridge inspections. Software is available to process and share that data in meaningful ways. While not an original goal of the project, the ability to

Under Review

process the drone data into bridge inspection deliverables is a key focus of this effort and is perhaps the most impactful result.

Phase III included the utilization of drones on 39 bridges of various sizes, types and locations. Case study inspection reports were compiled for a select number of bridges representative of various use cases. Those case studies can be found in Appendix A. A video summary of Phase III efforts can be found here.

Under Review

CHAPTER 2: UAS HARDWARE

2.1 Inspection-Specific Commercial UAS

Inspection specific drone technology is maturing, and several models now exist that serve the inspection and asset management industry. These drones include features important to bridge inspection such as sense and avoid, infrared imaging, autonomous flights, and collision-tolerant features. Each has their own strengths and weaknesses, but all can accomplish the task of obtaining high-quality data. As technology has improved, the focus has shifted from the hardware to the data. Hardware is still important, and opportunities exist for improvement, especially in regard to different payload items such as non-destructive testing equipment.

The primary data collection methods were from an imaging payload intergraded into the UAS body. Two UASs were selected based on observations from the Phase II study which identified two key features critical to UASs used in bridge inspection. The first was the imaging field of view needed to face vertically. This allows for inspection of members above the UAS such as deck soffit and interior beams. The second feature was the ability to fly without the need for a GPS signal. This is important when operating under a structure or in confined spaces.
Both UASs used are considered professional inspection-specific which set them apart from other off the shelf UASs. The quality of build, imaging payload, and flight software are industry-leading and crucial for proper safe inspection of bridge elements.

2.1.1 Mapping and Photogrammetry UAS

The team utilized the senseFly albris drone, which was designed for commercial inspection and mapping purposes. This model can fly under bridge decks, and the camera can view straight up. The albris UAS can be controlled interactively with a controller or autonomously with a pre-programmed flight. Both flight modes utilize a laptop computer to control the UAS. The flight control software contains the UASs settings, which include a real-time map that displays the drone's location, live image views, and flight data. The software can also be used to plan and monitor autonomous flights.

Under Review

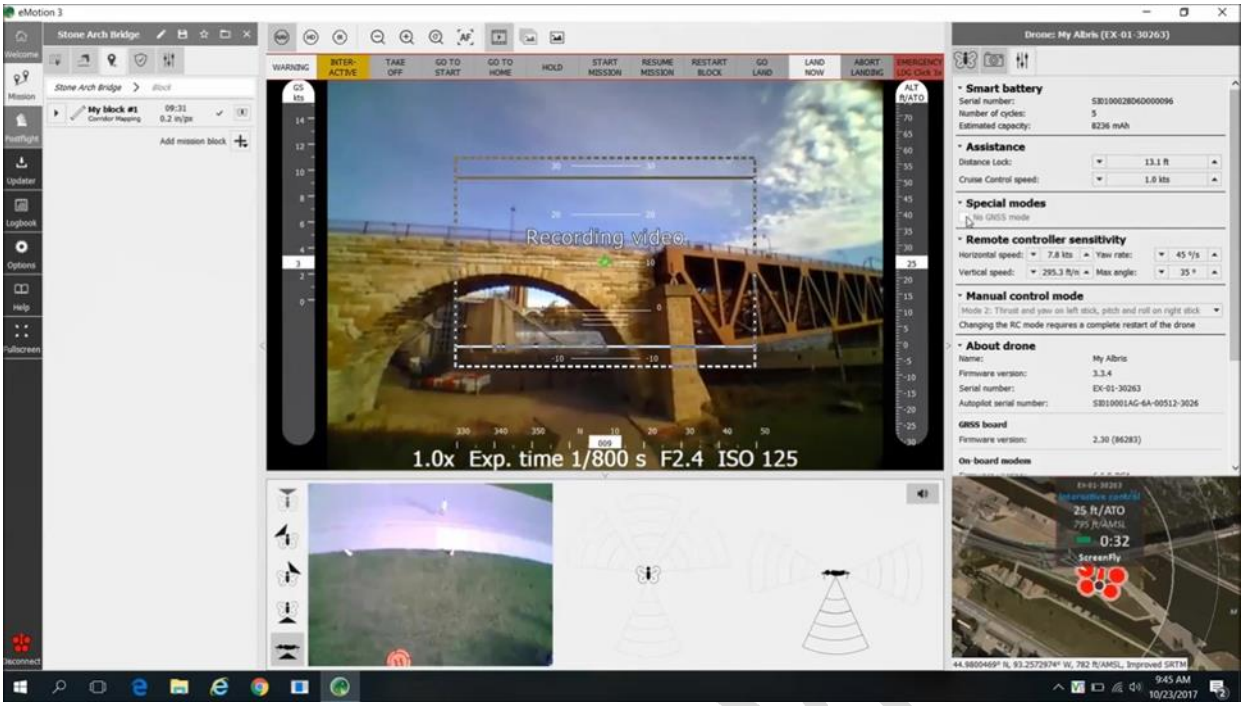

FIGURE 2.1 senseFly Emotion Software Flight Controls

This UAS was used in Phase II and selected again for Phase III given the overwhelming positive results. There have been a few changes to the albris hardware or software since the Phase II study, although the cost has decreased significantly since then. The UAS is approximately 22in by 32in by 7in and weighs 3.96lbs. This allows for easy handling and transportation. The batteries typically provide up to 20 minutes of flight time when operating under safe manufacturer guidelines. Flight hardware restrictions include wind speeds greater than 22 mph, range over 2.8mi away, or speeds in excess of 26mph.

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FIGURE 2.2 Image of the senseFly albris UAS.

The albris imaging payload consists of a TripleView head containing a high-definition video camera, a 38 Mega-Pixel (MP) still camera, and an infrared camera. The 38MP camera is the primary data acquisition tool. With pre-programmed or interactive flights, the albris can take still images at regular intervals which can then be processed by software to produce high-resolution images and models. The absolute horizontal/vertical accuracy of the UAS is reported at 3ft to 16ft without using ground control points and down to 0.04in when using ground control points.

Under Review

FIGURE 2.3 Example of albris High-Resolution Image Capability.

2.1.1.1 Commercial Inspection Specific Drones

As the market matures, other inspection specific UASs have become available. While this study did not compare all drones, it is important to understand what is available. The following is a list of know inspection specific drones available at the time this paper was published.

- senseFly albris
- Intel Falcon 8+
- DJI M200 Series

2.1.1.2 Collision-Tolerant UAS

As part of the Phase II study, it was identified that there are many areas within bridge inspection that are prohibitive for imaging using a larger mapping UAS. Additionally, these are often the same areas that are very difficult, or even impossible, for inspectors to gain visual or tactile access due to environmental hazards and entry restrictions. Examples of these types of restricted access locations are:

- Interior of tub girders, steel pier caps, and hollow abutments
- Culverts, pipes, or tunnels with or without water present
- Bridge deck soffit of large span bridges over water or heavily trafficked routes
- Web faces and top flanges of large span bridges over water or heavily trafficked routes

- High wall abutments
- Top of pier caps
- Bearings
- Vaulted spans

Several of these areas have safety concerns as well as access restriction. Some tub girder interiors, pier caps, and vaulted areas can be defined as confined spaces per Occupational Safety and Health Administration (OSHA), which require additional inspector training, equipment, and permits for confined space entry. Some of these locations can be imaged and post-inspected using a larger mapping and photogrammetry UAS from far away with a high-resolution camera; however, most of these are located where a camera would need to be within a few feet of the element being inspected. For these identified areas, the concept of a collision-tolerant UAS was selected for trial. Other options were considered to access these hard to reach areas with a smaller micro-UAS, larger propeller shrouds, or additional acoustic anti-impact sensors. The collision-tolerant was the most cost-effective option to move forward with.

The philosophy behind a collision-tolerant UAS is very different from that of the mapping and photogrammetry UAS. The design is built with object interference in mind. The operation is focused on using interaction with objects to help navigate, stabilize, and guide UAS through tight areas with or without line of sight. Designers at Flyability, a manufacturer specializing in collision-tolerant UAS's, identified this philosophy and created the Elios UAS based on this recognized need. Using a gimbal system and protective frame, the Elios can maintain flight during and after collisions with objects at speeds of up to 13 feet per second. The protective frame is carbon fiber rods and nodes in a geodesic polyhedron shape. The shape of the frame allows for impact absorption through deformation. The gimbal, which is the second key design feature, allows the frame to rotate 365 degrees in any direction. Along with the frame dissipating impact energy with deformation, the freely rotating frame allows energy to be dissipated with deflection. The video payload on the Elios consists of an infrared camera and a high definition video camera. Sample videos of a bridge inspection performed as part of this project can be found here:

Lakeville Bridge Inspection

St. Croix Crossing Pier Tower Inspection

Shakopee Pedestrian Bridge Beam Inspection

St. Paul High Bridge Confined Space Inspection

TH 55 Over Lake Street Bridge Confined Space Inspection

The collision-tolerant UAS was selected for use in the inspection of 10 bridges. At several of these bridges, the collision-tolerant UAS was used in conjunction with the larger mapping and photogrammetry UAS. The operation of the Elios was performed by a FAA licensed remote pilot and under FAA regulation. Set up and operation of the Elios was very simple, taking about 15 minutes. All flights were done interactively, meaning the pilot was under control of the UAS

Under Review

throughout the mission because the Elios is not capable of preprogrammed flight paths. The pilot navigated the UAS using a live video stream through a proprietary application on a tablet mounted on the remote control.

Recognized benefits of an inspection specific collision-tolerant UAS are the following:

- Easily piloted: UAS was easily operated by a pilot due to the ability to hit objects without fear of damage
- Ability to roll: The protective frame can serve as a rolling device to better control the UAS, save battery life, and maintain a fixed distance from the face of an object. It was ideal for inspecting wide flange beams and concrete deck soffits by rolling the UAS along the top side of the bottom flanges.
- Set-Up: Due to the simplicity of the equipment and interactive flight type, set up and site assessment are quick processes (typically 10-15 minutes).
- Lighting: The UAS is equipped with on-board lighting which is required due to fluctuating light/dark environments and proximity to elements.

FIGURE 2.4 Photograph of the Elios UAS Rolling Inside a Steel Box Beam

Recognized limitations of an inspection specific collision-tolerant UAS:

- Short battery life: The added weight of the protective frame and equipment reduces the allowable battery size, and thus reduces the battery life. A single battery operating under proper piloting conditions and operation yielded an average of 10 minutes of flight time, which limits its range and coverage.
- Video Interference: The protective frame is outside the video payload, meaning the frame will always be in the video partially obstructing the view.
- Air Flow and Debris: While operating in confined areas or near object surfaces, the UAS can create air flow eddies which affect the UASs flight. Additionally, operating in close proximities to surfaces kicks up dirt and debris which can damage the propellers and interfere with video quality.

The results of exploring the use of collision-tolerant UASs in bridge inspection were overwhelming positive. The relative ease of use and minimal set up make the collision-tolerant UAS a great addition to an inspector's tool box. Where limitations exist, time and experience can address with this specific drone. Compared to traditional methods of access, a collision-tolerant UAS can, at a minimum, 25% more cost efficient, safer for the inspector and the structure, and able to gain access to areas previously deemed inaccessible to an inspector.

2.2 Opportunities For Hardware Advancement

UAS hardware for bridge inspections have matured, and the ability to collect useful data is available and deployable. There still exists opportunities for improvement. The following improvements could reduce risk and increase the level of adoption by reducing the training and skill required to operate.

- Improved sense and avoid technology.
- More automated flight capabilities, especially in GPS denied environments.
- Improved battery life and reliability.
- Improved lighting or low light imaging capabilities.

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CHAPTER 3: DATA PROCESSING AND DELIVERABLES

Effective bridge inspections are comprised of three key components. The first component is the ability to detect deficiencies. To be successful in this endeavor, the bridge inspector's experience and knowledge play a key role. This research has demonstrated that a qualified inspector utilizing UAS can improve the ability to detect deficiencies by alternative access and utilizing high-quality images and infrared imaging.

The second component is the ability to document deficiencies. Traditionally this has been accomplished by documenting the inspection with detailed notes and photos. While this method has been effective, the results of this study have identified methods to improve the documentation of defects with the use of drone imagery in addition to the expanded use of terrestrial photos. 3D models and photo logs can be created with this imagery which greatly improves the ability to completely document inspections.

The third component of a successful inspection is the ability to clearly communicate inspection results to bridge owners, engineers, and decision makers. Traditional methods have included paper and electronic reporting. This research effort has demonstrated much more effective ways to communicate inspection data by employing recent advancements in the reality modeling of bridges and inspection data. These new methods are improving the ability for bridge inspectors to clearly communicate inspection results and ensure better translations of results for better decisions, which can help avoid oversights and save money. Recent advancements have also improved the ability to share the information with cloud-based inspection platforms that host the data for easy viewing.

The ability to collect and utilize large amounts of data is transforming our world. Drones have the ability to collect large amounts of data during bridge inspections. Processing software and inspection specific asset management platforms are giving engineers the ability to efficiently use this data to improve bridge inspections and are accelerating the ability to effectively manage these important assets.

3.1 Data Processing

3.1.1 Processing Inputs

3.1.1.1 UAS Images

All bridge inspections include some form of photo documentation, and digital cameras have improved the ability to document the inspection. However, the number of photos is usually limited to general overall photos and photos of specific deficiencies. If a large number of photos are taken during an inspection it becomes difficult to organize because each photo needs to be labeled with a description, location, and direction. Images from inspection specific drones are high-quality, and drones have the ability to collect a large number of images in a short amount of time. A typical UAS inspection can collect anywhere from 5 to 50 Gigabytes of data. Therefore, efficient processing and utilization of this data is critical.

Under Review

There is much focus on the image quality and the ability to detect deficiencies by viewing images taken with a drone. It is very difficult to quantify a minimum resolution or minimum camera parameters because the conditions encountered during an inspection differ widely. Image sensors and processing software have become sophisticated and it is difficult to rely on camera specifications alone. Our research has shown that the focus should be on the inspector's qualifications and their ability to determine on a case by case basis if the image quality is enough to determine with certainty the structural condition of the bridge element that is being inspected. In many cases, suspect deficiencies or areas should be followed up with a hands-on inspection. This is especially true when an inspector feels the need to use tools such as a hammer for sounding. For routine bridge inspections, there is no examination of an inspector's visual acuity, and this is not used as a metric for measuring the quality of bridge inspections. The exception is for NDT Certified inspectors to typically have their eyesight examined annually.

3.1.1.2 Terrestrial Photography

The task of capturing photographs from the ground has been routine for bridge inspection and will continue to be necessary. When considering the use of UASs in bridge inspection, it is important that the inspector be aware of the process and potential of using terrestrial photographs (photographs taken from the ground) in conjunction with aerial photographs to create high-resolution images and models. For several structures, imagery was taken from a point-and-shoot digital camera or action type camera. The method of taking photographs from these types of platforms is similar to aerial photography, in that the user needs to assure there is plenty of overlap as a series of photographs are taken. Additionally, it was found that the processing software worked better when images were taken in a smooth continuous path with approximately 75% overlap. The photographs taken can be used in the same programs as the high-resolution photographs from mapping missions. In conjunction with aerial photographs, they can provide a more comprehensive model as the final deliverable.

In several cases, terrestrial photographs alone were used to obtain high-resolution photographs and 3D models for post-inspection reviewing. The final results were positive and illustrated that the concept of photogrammetry in bridge inspection is a method which includes but is not limited to UASs. An example of the 3rd Avenue Bridge Pier Inspection can be found here.

Under Review

FIGURE 3.1 3D Model of Bridge Pier Created from Terrestrial Photos

3.1.1.3 Ground Control and Scaling

Another important input when creating bridge inspection deliverables are scales and/or ground control points (GCPs). The ability to accurately measure defects in the models is important. Generally, models created without these inputs can have an accurate scale within about an inch. However, to ensure accuracy, a scale can be placed before images are collected and can be used to check the accuracy or to manually scale the model.

Using GPS, a drone will place the model into the correct global position within several feet which is generally good enough for inspection purposes. The use of ground control points can add absolute accuracy and place the inspection model in the exact global position. Typically, these would be set by a land surveyor as aerial targets and their exact position would be recorded. These coordinates can be included in the model so when processed, the absolute accuracy can be set to as low as in millimeters. The accuracy depends not only on the precision of the actual GCP's, but also on the height at which the drone is flown. The lower the drone flies, the higher image resolution is.

Recently introduced to the market, are drone specific aerial targets that record their own position using GPS, which is processed and corrected to ensure survey grade accuracy. Our team used the Propeller Aeropoints with very good success. These targets allow for efficient and accurate manually entered control points which can be easily used on a majority of inspections.

Under Revi

FIGURE 3.2 AeroPoint Automated Ground Control Point Figure

3.1.2 UAS Reality Modeling Platforms

There currently exist many photogrammetry software packages available to process both drone and terrestrial images into useful and actionable data to document and communicate inspection results. For this study, we used Pix4D software which includes both a desktop and cloud version. The desktop and cloud version are integrated so that models created on the desktop version can be uploaded, processed and shared on the cloud version. These platforms process and create numerous outputs including the following:

- Orthomosaic Map
- GeoTIFF
- 3D Point Cloud
- 3D Textured Mesh
- Orthoplane
- Digital Surface Model (DSM)
- Digital Terrain Model (DTM)

Several platforms are available to process drone data including the following:

- Pix4D
- ContextCapture
- Recap
- Intel Insight
- Propeller

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The general workflow for a UAS inspection is as follows:

3.1.3 Deliverables

3.1.3.1 3D Models and Photo Logs

Reality modeling is the process of creating 3D photorealistic models from both drone and terrestrial images. The models generated are comprised of highly precise georeferenced point clouds and triangular meshes. The models can be used to measure deficiencies and can be annotated with inspection notes. Once a model is generated, the photos are located and referenced to the model. When the user clicks anywhere on the bridge model, the corresponding images of that area or bridge element are displayed. Therefore, the inspector no longer needs to create a photo log of the inspection, which can save a great deal of time during report generation. Traditional inspection photo logs are cumbersome, and time consuming to create and navigate. The reality model 3D photo log is easier to navigate and reference. It also creates a record of the bridge condition at a point in time so that as the bridge ages, deterioration rates can be observed.

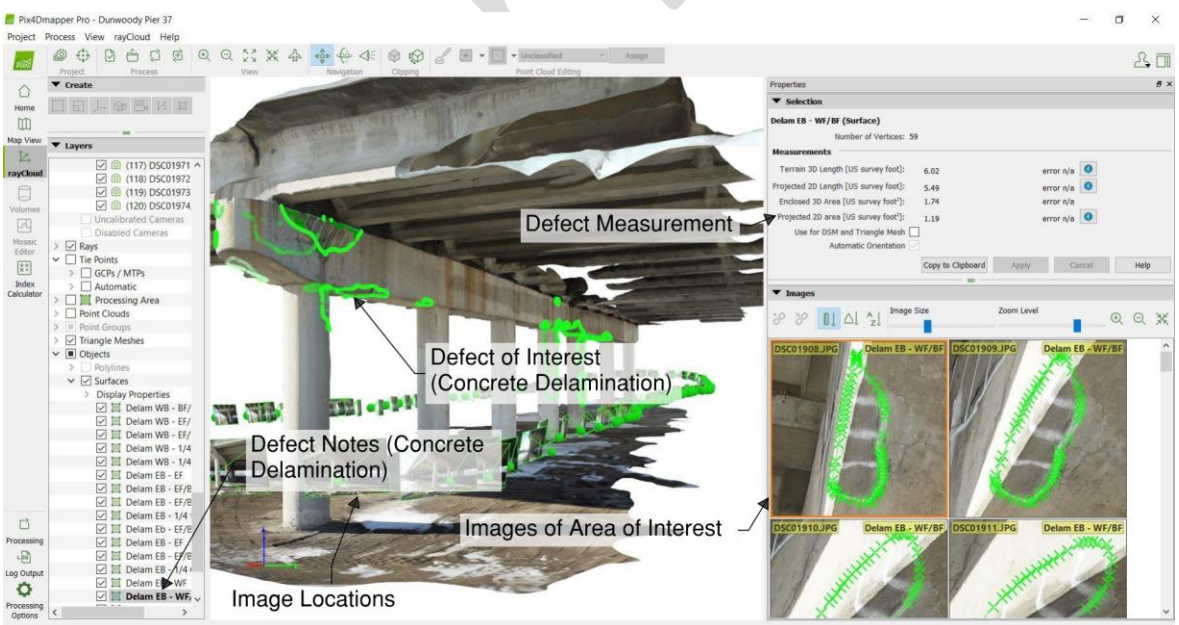

FIGURE 3.3 Pix4D 3D Reality Model Photo Log

FIGURE 3.4 Pix4D 3D Triangular Mesh

3.1.3.2 Orthomosaics and Orthoplanes

Other useful deliverables can be created in 2D formats including orthomosaics and orthoplanes. Both formats are simply large images that are created by combining individual images. An orthomosaic is a top down image that represents a map of an area and an orthoplane can be any planar surface such as a bridge façade or pier face.

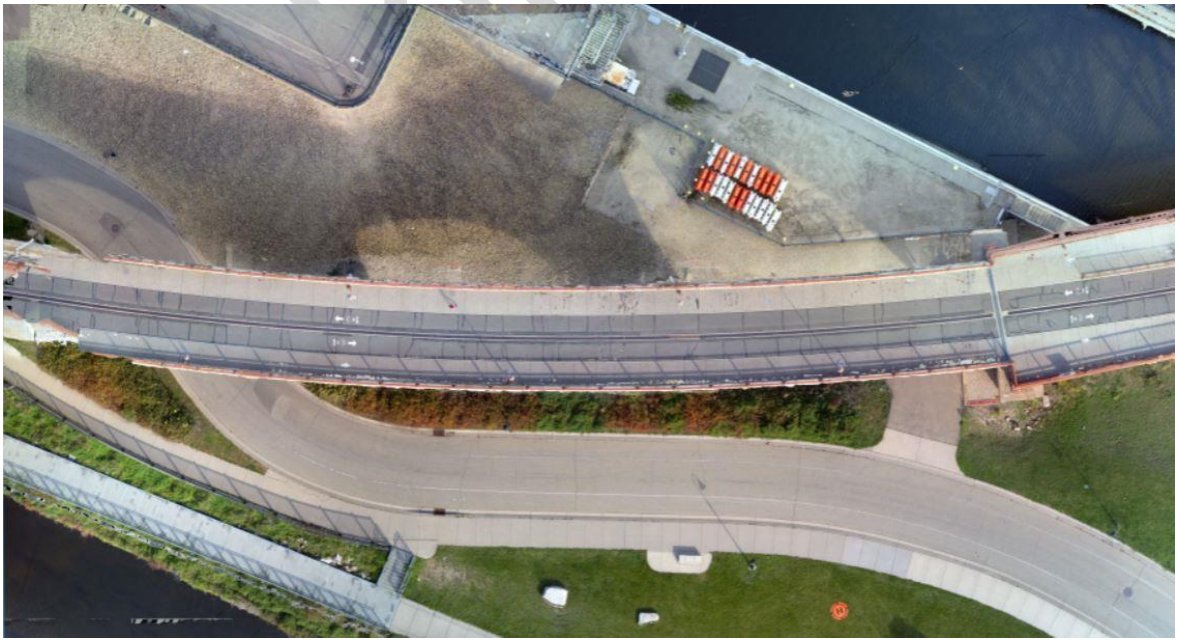

FIGURE 3.5 Orthomosaic of Bridge Site

FIGURE 3.6 Pix4D Bridge Facade Orthoplane

3.1.3.3 Cloud Sharing

The last component of a successful inspection is the ability to clearly communicate the inspection results. Performing bridge inspections with drones typically generates large amounts of data which can be difficult to share with bridge owners and decision makers, especially via email and ftp sites where company firewalls may exist. The solution lies in the ability to share inspection results on cloud-based platforms. Using the cloud interface, a bridge engineer or owner can view the inspection data in 3D models without having to download and store large amounts of data.

FIGURE 3.7 Cloud Virtual Inspector

Below are hyperlinks to bridge models from this project that are shared on the web platform:

Stone Arch Bridge
https://cloud.pix4d.com/pro/project/262981/3d?shareToken=db3d5be0e4fc4b8687aba5bd2bb48ba1

Dunwoody Bridge Pier 37
https://cloud.pix4d.com/pro/project/265642/3d?shareToken=3aec98c6fc1b4fa88537eb4f2292015f

Lakeville Bridge
https://cloud.pix4d.com/pro/project/164949/3d?shareToken=e48e6ce380a047f5a3e92d083299d23b

Dunwoody Pier Model

https://cloud.pix4d.com/pro/project/263323/3d?shareToken=6fba4bbc2e4a443f9029a71b72666f65

Washington County Bridge Deck Delamination Survey

https://cloud.pix4d.com/pro/project/153881/mesh?shareToken=cacccbaa7032478d9bd4ce102b4860dc

St. Croix Crossing Box

https://sketchfab.com/models/23418bbd1efe4069aa7b6668e5ddb161 https://youtu.be/Gxf1NLQqDHc

South St. Paul Retaining Wall Inspection

https://cloud.pix4d.com/pro/project/202326/map?shareToken=aa9bc85840f2402f902aa9ca622932e6

3rd Avenue Bridge Pier

https://skfb.ly/6t86G

Freeway Corridor and Bridge Deck Survey

https://cloud.pix4d.com/pro/project/187948/mesh?shareToken=c0a7484219044a908fe65250bf47c74c

CHAPTER 4: COST ANALYSIS

Traditional access methods for bridge inspection include Under Bridge Inspection Vehicles (UBIV), man lifts and rope access. UBIV's can cost from $500,000 to $1,000,000 to purchase and per day costs range from $2,000 to $3,500 per day. With the use of this inspection equipment traffic control is also often required in the form of lane or shoulder closures. Traffic control can cost from $500 - $2500 per day. These costs can make up a significant portion of the total inspection costs for larger bridges. The use of drones for bridge inspection can offset some or all of these costs depending on the bridge configuration and location. For smaller local bridge routine inspections where access equipment and traffic control are not needed, utilizing drones may increase the overall cost of the inspection slightly but, the inspection deliverables are greatly improved.

Bridge inspection reports in Appendix A include detailed cost comparisons between tradition inspection and access methods with UAS assisted inspection. For bridges where access methods such as UBIV's, lifts, rope access are required the cost savings can be significant. The following assumptions were used in determining the cost savings:

Under Review

For the selected case studies presented in the Appendix the average cost savings was 40% which is significant. A summary of the cost analysis for each individual bridge is summarized below:

Structure	Traditional Inspection Cost	UAS Assisted Inspection Cost	Savings +/-	Savings Percentage
19538	$1,080	$1,860	-780	-72%
4175	$15,980	$13,160	2,820	18%
27004	$6,080	$4,340	1740	29%
27201	$2,160	$1,620	540	25%
MDTA Bridges	$40,800	$19,800	21000	51%
2440	$2,160	$1,320	840	39%
27831	$2,580	$540	2040	79%
82045	$2,660	$1,920	740	28%
92080	$2,580	$1,350	1230	48%
92090	$2,410	$1,570	840	35%
62504	$3,660	$1,020	2640	72%
82502	$3,240	$2,400	840	26%
			Average Savings	**40%**

APPENDIX A Cost Comparisons Between Tradition Inspection and Access Methods with UAS

The quality of a hands-on versus a drone inspection is difficult to generalize and must be determined by a qualified inspector on a case by case basis. Typically, a hands-on inspection will provide more confidence in the inspection results but in many cases the quality of a drone inspection is enough to determine with confidence the condition of the bridge and defect detection is comparable. The quality of the deliverables in most cases is improved with the use of drones and the communication of the inspection results is also improved. The quality of the deliverables should also be considered when determining what access method is appropriate for each individual bridge.

It is relatively easy to determine the cost savings associated with actual inspection costs. It is much more difficult to determine the cost savings associated with improved deliverables. The improvement of deliverables may have an even larger impact on cost savings. Bridge owners and engineers must make risk-based decisions on repair, replacement and maintenance needs for a bridge. With improved inspection information bridge owners can make better decisions which leads to better investments in their bridges.

CHAPTER 5: SAFETY IMPROVEMENTS

While using a drone during a bridge inspection creates minor risks associated with the risk of crashing the drone into a person, vehicle or airplane. Because of the very low altitude of flights needed for bridge inspections the risk of a collision with an airplane is almost non-existent when using commercial quality drones that control the risks of an uncontrolled flight. These risks are offset by a dramatic reduction in risks for the public and inspection personnel. Roadway work zone risk pose significant safety hazards for the public and transportation workers. The Federal Highway Administration has a Work Zone

Under Review

Management Program that deals with work zone safety. A work zone crash occurs every 5.4 minutes in the United States. In 2014 669 fatalities occurred in work zones and unfortunately the trend is an increase in crashes as distracted driving is becoming more prevalent.

There are no statistics specifically associated with bridge inspections but accidents and fatalities resulting from bridge inspections are not uncommon. There is some risk associated with the use of bridge inspection equipment and working at heights, but the largest risk factor is associated with working near traffic and in shoulder and lane closures. Drones can be utilized during bridge inspections to reduce or eliminate the need for traffic control and the need for inspection personnel to work near traffic. Bridge owners should consider the use of drones when the risks to the public and inspectors can be reduced while considering the inspection quality and condition of the bridge. For low risk bridges the use of drones should be considered even when reduced inspection quality is expected if there is a significant improvement in overall safety. While traditional access methods will continue to be needed the use of drones for bridge inspections are underutilized by bridge owners and safety gains can be realized with the increased use of drones.

Under Review

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Cost

Bridge inspection costs can be reduced with the use of drones. UBIV's cost anywhere from $500,000 to $1,000,000 to purchase, and rental costs per day range from $2,000 to $3,500 with an operator. Inspection-specific drones cost anywhere from $15,000 to $40,000. Bridge owners should consider the use of drones where costs can be reduced without a reduction in inspection quality. Traffic control is also expensive and can range from $500 to $2,500 per day, which can be reduced or eliminated with drone integration. Appendix A includes a cost analysis for representative bridges considered in this research effort. The overall average cost savings was 40%. Where there were no cost savings exhibited, the quality of the deliverables was greatly improved. More difficult to quantify is the cost savings realized where improved data leads to more informed decisions on investments in bridges maintenance, repair, and rehabilitation. While difficult to compute, these cost savings are likely greater than realized with the reduction of expensive access methods and traffic control.

6.1.2 Improved Deliverables/Reality Modeling

Traditional bridge inspection results are typically compiled in a tabular format supplemented with images by average definition hand-held cameras. Drones and related processing software have given engineers the ability to collect large amounts of data and process it into actionable information cost or a model that relates the calculated dollar value to the costs of input effectively. The tabular data consist of bridge inventory items, bridge elements and their quantities, and defects. Drones and related processing software have given engineers the ability to collect large amounts of data and process it into actionable information cost effectively. Utilizing drone technology allows inspectors to communicate bridge inspection results in a more graphical manner, which can be is more easily reviewed and understood by bridge owners and engineers. The tabular data is important and will remain an important part of the inspection, but by communicating the results in a 3D manner, is it allows inspectors to better generate better data and by giving the inspector the ability to generate more accurate quantities. For instance, a concrete spall can be drawn directly on a model to get a very accurate measurement. This ability to better communicate results through reality modeling allows for improvement in managing assets and provides better information that was previously not available.

6.1.3 Collision Tolerant/Confined Spaces

One of the main objectives of this phase of research was to identify and test a drone technology that would allow for the inspection of very tight and confined spaces. The team identified and extensively tested the Flyability Elios collision-tolerant drone. Multiple applications included several confined space inspections in steel and concrete box beams and pier towers. Another application that proved very effective was the ability to inspect between beams for multi-girder bridges and bearing inspection for beam bridges. Beam bridges are low risk due to their load path redundancy, so many do not require a hands-on inspection. As such, the cost to inspect beam bridges is prohibitive. The collision collision-tolerant drone may not reach the quality of a hands-on inspection since the inspection is by viewing video,

Under Review

but the overall effect is a much-improved inspection for a low cost when compared to an inspection that is performed from the ground.

6.1.4 Safety

With over 60 bridges inspected to date, the project shows that the use of drones for bridge inspection can reduce safety risks and this can be accomplished in two ways. The first is the ability to reduce risk by removing or reducing the need for traditional access methods such as UBIV's, rope access, ladders and scaffolding. Those traditional access methods will still be necessary, but the use of drones can reduce their use to the short term, which reduces risk to bridge inspectors. The second opportunity to reduce safety risks is the elimination or reduction in traffic control. There is a significant risk to both the public and bridge inspectors when lane and shoulder closures are needed to complete a bridge inspection with traditional access methods such as UBIV's. Compounding this issue is the rise of distracted driving, which increasing this risk.

6.2 Recommendations

Based on the research work of this phase, the following recommendations are presented:

•Drone use should be considered as part of a risk- based approach to bridge inspection where safety, cost and quality improvements can be realized.

•Safety risks can be reduced for both inspectors and the public. Much of the focus has been on the safety of flying a drone, but the emphasis should be on reducing the risk of the overall inspection.

•Collision-tolerant drones should be considered for confined space inspections where access and safety can be improved without a reduction in inspection quality.

•Collision-tolerant drones should be considered for the inspection of multi-beam bridges, especially when a hands-on inspection is cost prohibitive.

•Many of the same improved deliverable benefits can be realized by utilizing terrestrial digital cameras. Models of specific bridge components such as piers can be generated in combination with a drone or by themselves.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Jennifer Wells. Author, Barritt Lovelace. Author; data collection: Jennifer Wells. Author, Barritt Lovelace. Author; analysis and interpretation of results: Jennifer Wells. Author, Barritt Lovelace. Author; draft manuscript preparation: Jennifer Wells. Author. Barritt Lovelace. Author. All authors reviewed the results and approved the final version of the manuscript.

Under Review

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Under Review