Unmanned Aircraft Systems (UAS) Impact on Operational Efficiency and Connectivity

Final Report

by

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DISCLAIMER

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16. Abstract

Over the last several years, the use of unmanned aircraft systems (UAS), commonly referred to as drones, has increased significantly. This report outlines the findings of a study to explore the benefits of UAS technology when deployed at the SCDOT, specifically focused on the areas of land surveying and bridge inspection. The results of a drone-based land survey experiment found that given common field conditions, survey points could be within 0.68cm (.022 feet) (XY), 0.09cm (.003 feet) (Z) and 1.46cm (.048 feet) (XYZ) of the true location. As a natural extension of this experiment, it was found that computed stockpile volume estimates ranged between 1.5% and 3.3% of actual. To evaluate how effective UAS where at supporting bridge inspections, a test bridge was inspected twice using two different bridge inspection engineer (BIEs). Over 90% of the inspection points could be sufficiently observed using a drone. A significant advantage of drone deployment was the reduced need for under-bridge inspection trucks (UBIT), convenient documentation, keeping the BIEs away from traffic and the process being nearly invisible to the traveling public. The experiment also found an estimated cost savings of approximately $1,500 due to the reduced need for UBIT and traffic control. Limitations of the technology included the lack of tactile contact, observing deficiencies at difficult angles near obstructions and flying in GPS denied environments. The BIE felt that the advantages of the technology outweighed the limitations and supported further investigation in the future. This report also elaborates on a proof of concept experiment conducted to evaluate the possibility of inspecting a bridge remotely via a 4G cellular live stream broadcast. The remote BIE felt that this was a successful workflow and that this technology could be used to inspect bridges successfully with similar advantages and limitations previously described. It was found that inspecting bridges remotely added additional complications to the process including insufficient connectivity to stream the video, excessive latency in video and voice command and the reliance on leading-edge hardware and software that was not always reliable.

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TABLE OF CONTENTS

List of Tables

List of Figures

EXECUTIVE SUMMARY

Over the last several years, the use of unmanned aircraft systems (UAS), commonly referred to as drones, has increased dramatically. Over one million drones are registered with the Federal Aviation Administration (FAA), with this number expected to grow to seven million by 2020 (Essex, 2016). The growth of the UAS market and advancements in technology have significantly driven down the cost of many high-functioning aerial platforms. The reduced cost, coupled with the relaxation of FAA regulations, has opened many opportunities for state departments of transportation (DOTs) to incorporate this technology into their operations. A 2017 study supervised and funded by the World Road Association (formally PIARC) found that many governments around the world, as well as state DOTs, have "…used this technology successfully in various fields" and that there is "huge potential for UAS applications" (Rednoa, 2017). The Florida DOT (FDOT) reaffirmed this position in a study commissioned to explore how a custom UAS could improve their asset management program (Bridge and Ifju, 2018). This report outlines the findings of a study to explore the benefits of UAS technology when deployed at the SCDOT. Specifically, this study focused its efforts on evaluating drones for surveying, and as an extension of that, the use of drones for stockpile volumetric calculations. Additionally, the study explored the use of drone technology to augment and support traditional bridge inspection workflows. Part of that evaluation was a proof of concept study on the practicality of using drones to inspect bridges remotely through live stream broadcasting over a cellular 4G network.

The published literature strongly suggests that UAS technology has the opportunity to support land survey activities at state DOTs. However, before the SCDOT can adopt the technology for this purpose, a clear understanding of accuracy is needed. To support this effort, a structured experiment was conducted using multiple commercially available aircraft and software packages. Thirty-one aerial targets were located over a 14,000m^2 (3.46 acre) site. Half of the targets were used to create the survey and the other half to test accuracy. Two common commercial UAS were used in the experiment. Data was acquired at three altitudes and repeated three separate times. The study found that given the conditions of this experiment, survey points could be within 0.68cm (.022 feet) (XY), 0.09cm (.003 feet) (Z) and 1.46cm (.048 feet) (XYZ) of the true location. The study also found that models created from different images captured at the same altitude had some variability in point locations that ranged from as little as 0.75cm (.025 feet) to as much at 3.94cm (.129 feet) in the XYZ direction.

As a natural extension of testing drone-based surveys, this study also evaluated the accuracy of stockpile volume estimates from photometric models. A two-phase experiment was conducted with the same aircraft and software used in the survey experiment. In the first phase, a large cardboard pyramid with a known volume was used to simulate a stockpile. Using georeferenced images collected by a Phantom 4 Pro drone and the structure from motion (SFM) software ContextCapture, the computed volumes ranged between 1.5% and 3.3% of the actual volume. In the second phase of the experiment, a photometric survey was created of a large SCDOT borrow pit. The volumetric calculations were computed using conventional survey practices and with drone collected images. There was a 9.8% difference between the two methods with the drone base model providing significantly higher model resolution and a number of data points.

The cornerstone objective of this study was to evaluate the effectiveness of using UAS to augment and support traditional bridge inspection methods in South Carolina. A concrete test bridge over a large river was selected for the experiments. When inspecting the test bridge using traditional methods, a under bridge inspection truck (UBIT), a mobile crash attenuator trailer, traffic management signage, and 10 people were required.

To evaluate the effectiveness of using a UAS to support a bridge inspection team, two primary experiments were conducted using the same test bridge. The purpose of the first experiment was to evaluate how many of the defects the drone could identify given optimal conditions. For this experiment, the bridge inspection engineer (BIE) that recently inspected the test bridge using a UBIT was tasked to re-inspect the bridge using only the drone. The BIE had access to the previous inspection report so the deficiencies were known. The results gave the researchers an understanding of the maximum amount of deficiencies that could be sufficiently observed given optimal conditions. Essentially, could a BIE find a deficiency if they knew it was there? The second experiment was designed to evaluate the number of deficiencies that could be identified given real-world conditions when the deficiencies were not known. For this experiment, a second BIE from another district who was unfamiliar with the test bridge was given the same drone inspection task.

After the two experiments, the overall opinion of both BIE crews of the technology was positive. Over 90% of the inspection points could be sufficiently observed using the drone. A significant advantage of drone deployment noted by the BIEs was the reduced need for a UBIT. The deployment of a UBIT often requires closing a lane of traffic and placing BIEs in harm's way. Operating a UAS can be done away from traffic and be invisible to the traveling public. With the experiments conducted, the time needed to conduct the inspection with the drone was equivalent to that of traditional methods with inspection speed increased throughout the inspection. It is expected that as this was the first time the BIEs had used the technology, as it becomes more commonplace, UAS inspections time will decrease significantly. Drone technology also made documentation of the bridge convenient. Recording still images and video is a natural use case for UAS and it was easy for the BIE to document as-built conditions. An order of magnitude cost estimate was created for inspecting the bridge using traditional methods and when using a UAS. It was found that deploying the UAS would have an estimated cost savings of $1,500 for this test bridge.

Despite the advantages, there are still several significant limitations of the technology that at present can only be met by in-person inspections. One example is that with traditional inspections, tactile contact with the structure is required. This includes chipping away loose concrete or rust and also sounding out materials such as with woodpiles. Another limitation is the difficulty in flying under bridges where GPS signals are blocked. When GPS is available, especially when a RTK ground station is used, commercially available UAS are able to hold a static position with very little drift even in the presence of moderate wind. However, under a bridge, the GPS signal is lost and the aircraft is susceptible to drift. Onboard accelerometers and proximity sensors help stabile the system, but flight control is challenging even for seasoned pilots. However, the researchers found that much of the inspection could be performed under and to the side of the bridge, where GPS signal can be established. From this position, zooming the camera at an upward angle makes much of the underside of the bridge visible. Taller bridges allow for a more aggressive angle improving the field of view. It was also observed that using lower-cost drones may be more advantageous than higher performance rigs with high powered zoom cameras. Lower-cost units would need to fly closer to observe the bridge sufficiently which increases the risk of collision; however, that risk is offset by the lower cost to replace the UAS. Bridges with vegetation around them also limit the value that a UAS would provide the workflow. Even with GPS lock established, a small branch, which may not be detected by onboard sensors or visible in the pilot's first-person view screen could cause a crash if it collides with the propellers.

This report also elaborates on a proof of concept experiment conducted to evaluate the possibility of inspecting a bridge with the BIE located off-site. The remote inspection experiment was very similar to the two bridge experiments previously described. The crew was made up of a pilot who commanded the aircraft, a co-pilot who controlled the camera and a third person who replaced batteries and managed the logistics of the site. The BIE was located at their home office approximately 30 miles away. The flight crew live-streamed the video using two different commercially available apps. The flight crew and BIE communicated by phone or through the app. After the experiment, the onsite flight crew and the remote BIE felt that this was a valuable tool. They believe that this technology can be used to inspect bridges successfully with similar limitations as described in experiment #1 and #2. Inspecting bridges remotely added additional complications to the process, however. These complications include insufficient connectivity to stream the video, excessive latency in video and voice command and the use of additional technology that is not completely reliable.

CHAPTER 1

Introduction and Current UAS Deployment with State DOTs

1.1 Unmanned Aircraft Systems

UAS originated with Great Britain's development of the first pilotless aircraft in the early 1900s. Drones have been deployed in the military for decades and recently small UAS have gained popularity in the public sector (Dronethusiast, 2019). There are two categories of UAS – model and non-model. Model aircraft owners are considered recreational users, whereas non-modelers use UAS for commercial purposes. The commercial use of drones started to gain traction in 2006 when the FAA issued its first commercial permit. Still, adoption remained slow with an average of only two new commercial permits issued by the FAA per year until 2014 (Desjardins 2016). However, interest accelerated after Amazon revealed in 2013 that it was investigating the use of drones for delivery (Dronethusiast, 2019).

Accompanying the increasing popularity of UAS was the development of federal regulations regarding their use. In 2005 the FAA issued basic UAS guidelines and subsequently in 2007 the agency implemented policies for the operation of UAS. These regulations required all commercial operators to obtain a Certificate of Waiver or Authorization (COAs) for specific drone use – a process that was difficult and time-consuming (Speicher, 2016). Public pressure to improve the process influenced the government to pass the Reform Act of 2012 requiring the FAA to develop more effective drone policies and regulations for commercial UAS. After several years of public input and research, the FAA published Part 107 for the Title 14 Code of Federal Regulations governing UAS use, operation, and certification in 2016 (Federal Register). Subsequently, in 2017 the FAA initiated their Integration Pilot Program (IPP). This program was developed to bring public and private interests together to identify additional UAS operations, address security and privacy issues, and accelerate safe drone integration into the National Airspace System (FAA, 2017).

By the end of 2018, the number of recreational drones in the U.S. reached an estimated 1.6 million and the commercial fleet expanded to more than 110,000 with strong growth expected to continue. By 2022 the FAA forecasts that the number of recreational drones will increase to 2.4 million and the fleet of registered commercial drones will climb by more than 400% to greater than 450,000 (FAA 2018a). Globally, annual spending for unmanned aerial systems is expected to double to 11.5b over the next decade (Grey et. al., 2018).

To fly a commercial drone the operator must obtain a Remote Pilot Certification from the FAA and by mid-2018 more than 100,000 pilots had been certified. To support the expanding commercial use of UAS the number of certified remote pilots is expected to grow to more than 400,000 by 2022 (Plaza 2018, FAA 2018a). The FAA 2018a report noted that commercial UAS were used primarily to collect data and aerial images. Primary usage included real estate photography (48%), industrial and utility inspection (28%), agricultural applications (17%), and state DOT and local governments (3%) (FAA, 2018a).

Research on the use of UAS has shown how effectively implementing drones into commercial uses can improve safety, efficiency and provide cost savings (McGuire et.al., 2016). The realization of the potential of this technology has created a surge in the adoption of drones into commercial and public operations. This substantial growth has helped fuel demand, increase competition, and thus lower the price of capable drone systems. One of the fastest growing sectors has been the construction industry which experienced a 239% increase in drone use in 2017 (Zitzman, 2018).

1.1.1 Unmanned Aircraft Systems and Transportation Infrastructure

The World Road Association published a research report entitled A Report on the use of UAS to Remotely Collect Data for Road Infrastructure in 2017 (REDNOA, 2017). This report forecast 'huge potential for UAS applications' in roadway infrastructure. An American Association of State Highway and Transportation Officials (AASHTO) study was conducted by Ni and Plotnikov in 2016. The results of this study entitled The State of the Practice of UAS Systems in Transportation found that 17 state agencies had studied, or were currently using drones, in some aspect of their operations. Another sixteen states were exploring or supporting drone research (Ni and Plotnikov, 2016).

A subsequent AASHTO study by Ni and Plotnikov two years later in 2018 found that state DOT interest in drones had increased. Thirty-five of the forty-four states (80%) participating in the study were currently using or exploring the use of drones. Twenty state DOTs had integrated drones into their operations and another fifteen states were conducting research and/or testing to determine possible drone applications (Dorsey, 2018).

The investigative efforts and operational deployment of UAS (drones) by state transportation agencies have continued to expand. Numerous studies by universities, state DOTs, and federal agencies have been conducted to determine current interest and application by state DOTs. However, the methodology of the studies is not consistent and the participation rate is never 100% of the 50 state DOTs. These limitations make it difficult to gain a comprehensive understanding of the current use of drones by DOTs throughout the United States from any one study.

To obtain better insight some DOTs have developed summaries that combine the findings from several of the studies (MoDOT, 2018; MDT, 2018; ODOT, 2016). Building on those earlier efforts this research team reviewed fifteen (15) recent studies and publications to further expand the coverage of state DOTs regarding drone research and use (AASHTO, 2016; AASHTO, 2018; Capers, 2018; Dorsey, 2016; Gillins et al., 2018; Lercel and Steckel, 2018; Lillian, 2018; Maguire and Dorafshan, 2018; McGuire et al., 2016; MoDOT, 2018; MDOT,2018, Ni and Plotnikov, 2016; REDNOA, 2017; ODOT, 2016; UTDOT, 2017). The combined findings of these studies and publications are summarized in table 1.1.

Table 1.1: State DOT research and deployment of UAS

State DOT	Deployed	Research	State DOT	Deployed	Research
Alabama		X	Montana	X	
Alaska	X	X	Nebraska	X	X
Arizona	X		Nevada	X	
Arkansas	X		New Hampshire		X
California	X	X	New Jersey	X	X
Colorado	X	X	New Mexico		X
Connecticut	X	X	New York	X	X
Delaware	X	X	North Carolina	X	X
Florida	X	X	North Dakota		X
Georgia	X	X	Ohio	X	X

State DOT	Deployed	Research	State DOT	Deployed	Research
Hawaii			Oklahoma	X	
Idaho	X	X	Oregon	X	X
Illinois	X	X	Pennsylvania	X	
Indiana	X	X	Rhode Island	X	X
Iowa	X	X	South Carolina		X
Kansas	X	X	South Dakota		X
Kentucky	X	X	Tennessee	X	
Louisiana		X	Texas	X	X
Maine	X		Utah	X	X
Maryland		X	Vermont	X	X
Massachusetts		X	Virginia	X	X
Michigan	X	X	Washington	X	
Minnesota	X	X	West Virginia	X	
Mississippi	X		Wisconsin		X
Missouri	X	X	Wyoming		

Data on drone activity in the noted publications were available for all but two states, Hawaii and Wyoming. Of the remaining forty-eight (48) state DOTs, all had deployed and/or were researching (investigating) the application of drones for their DOT operations. Thirty-eight (79%) of the 48 states indicated that they had operationally deployed UAS for one or more activity and twelve (21%) were researching/investigation possible application(s).

Most every study over the past three years has shown increasing interest from state DOTs for the investigation and/or incorporation of drone technology into their operations. The elevated interest in UAS is largely fueled by the growing list of possible applications and the technology's allure for improved safety, increased efficiency for the collection of data, and lowering operational cost (Dorsy 2016, Dorsey 2018).

1.1.2 Unmanned Aircraft Systems Uses in State DOTs

As noted in table 1.2, Statista (2018) categorizes the commercial use of UAS into six groupings: photography (34%), real estate (26%), construction (26%), agriculture (21%), emergency management (8%), and insurance applications (5%). AidVid initiated a listing of commercial drone uses in 2014 which has subsequently grown to over one-hundred forty uses in twenty categories ranging from photography to weather atmospheric studies (AirVid, 2018).

Table 1.2: UAS commercial uses.

UAS Use Categories	%
Photography	34%
Real Estate	26%
Construction	26%
Agriculture	21%
Emergency Management	8%
Insurance	5%

A number of the uses noted in AidVid's listing have applications for the development and management of transportation infrastructure. The twenty states noted in Ni and Plotnikov's 2018 study of state DOTs that had incorporated drones were using them for a variety of functions, including aerial photography, surveying, public education/outreach, bridge inspection, emergency response, pavement inspection, scientific research, traffic control/monitoring, and high-mast light pole inspection. The number of these states that were deploying drones for each of these operational activities is shown in figure 1.1.

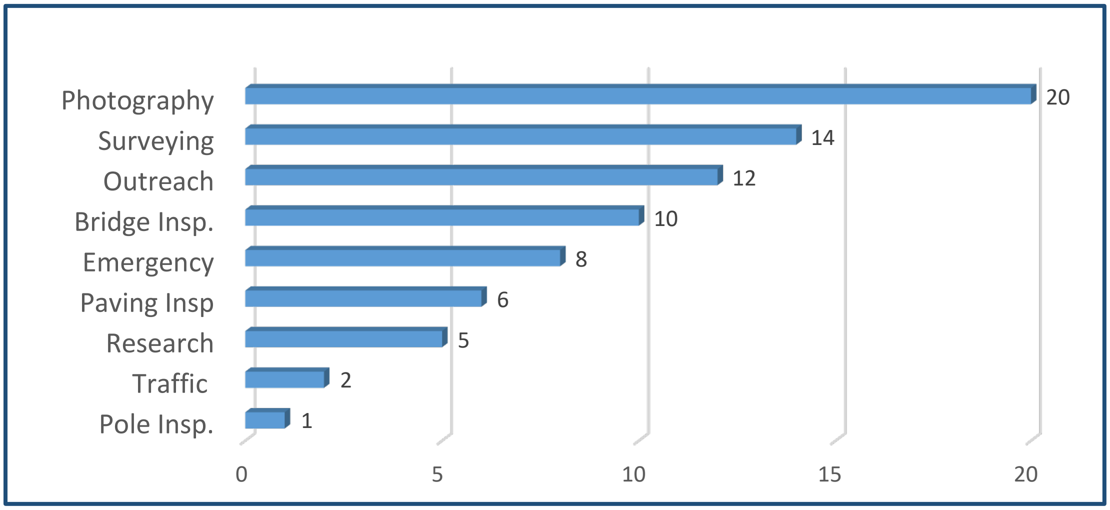


Figure 1.1: States incorporating each drone use.

An examination of the fifteen publications and studies utilized to develop the listing of state DOT deployment and research of UAS (table 1.1) reveals a variety of agency uses that have been organized (categorized) using several different approaches. Representative categories include traffic monitoring, structural inspection, construction inspection, documentation/monitoring, survey and mapping, and others. The categories and associated are summarized in table 1.3

Table 1.3: Categories of UAS use.

Category	Application/Use
Traffic Monitoring	Traffic Surveillance, Identifying Congestion, Traffic Counts
Structural Inspection	Bridges, High-mast Poles, Radio Towers, and Other Structures
Construction Inspection	Progress Monitoring, Safety, Environmental Compliance, Quantity & Volume Calculations
Document/Monitor	Photography, Videography, Environmental Issues
Survey & Mapping	Topographical Surveys & Mapping, Modeling
Other Applications	Emergency Response, Search/Rescue, Accident Investigation, Wildlife Monitoring, Marketing & Outreach

As noted in the prior studies, thirty-eight (38) state DOTs, have deployed UAS in their operations. The category of drone usage for each of these states is summarized in table 1.4. The most common usage for the thirty-eight state DOTs was ‘Survey and Mapping’ which was noted as used by 28 of the state DOTs. Close in utilization was ‘Structural Inspections’ with 27 DOTs identified as employing UAS technology. Drones were used for ‘Traffic Monitoring’ in eleven state transportation agencies while 'Construction Inspection' and 'Document/Monitoring' were used by eight and seven states respectively.

Table 1.4: State DOT use of drone technology.

State	Category						
DOT	Traffic Monitor	Struct. Inspect	Constr. Inspect.	Doc. / Monitor	Survey Mapping	Other Apps	# Uses
Alaska		X			X		2
Arizona		X			X		2
Arkansas	X						1
California		X			X	X	3
Colorado				X	X		2
Connecticut		X					1
Delaware	X			X			2
Florida		X			X		2
Georgia	X		X	X	X		4
Idaho		X			X		2
Illinois		X	X		X	X	4
Indiana			X				1
Iowa		X			X	X	3
Kansas		X	X			X	3
Kentucky		X			X	X	3
Maine		X			X		2
Michigan	X	X		X	X	X	5
Minnesota	X	X			X	X	4
Mississippi					X	X	2
Missouri		X					1
Montana		X	X		X		3
Nebraska		X			X		2
Nevada					X		1
New Jersey	X	X		X	X	X	5
New York			X				1
North Carolina		X		X	X	X	4
Ohio	X	X		X	X	X	5
Oklahoma		X			X		2
Oregon		X			X	X	3
Pennsylvania					X		1
Rhode Island							0
Tennessee					X		1
Texas	X	X	X		X	X	5
Utah		X	X		X	X	4
Vermont		X		X			2
Virginia	X						1
Washington	X				X	X	3
West Virginia	X		X		X		3
Totals	11	27	8	7	28	15	

Based on the findings from the fifteen studies, twenty-eight of the state DOTs had utilized drones for more than one category/use, including nine (9) state agencies that have deployed operations in four (4) or more categories of use. The adoption of drone technology by state DOTs has gained significant traction over the past 3 years (Lillian, 2018; AASHTO, 2018).

1.2 State of the Practice of State DOTs UAS Deployment Methodology

1.2.1 Study Objective

The fifteen cited studies and publications provide the support that UAS are being investigated and/or deployed in a vast majority of the state transportation agencies. However, all of the cited studies involve a limited sample size and most provide minimal insight regarding UAS program development and the extent of use in the transportation agency's daily operations. In addition, the pace at which drone technology is being adopted limits the relevancy of studies/publications dated only a few years earlier. Therefore the objective of this study was to:
Investigate the level of UAS program development and the degree to which drone technology has been incorporated into the daily operations of state transportation agencies that have broad exposure to the spectrum of UAS uses.

1.2.2 Methodology

There are nine (9) states identified in table 1.4 that have experience with UAS in four or more operational categories. These nine states include Georgia (GA), Illinois (IL), Michigan (MI), Minnesota (MN), New Jersey (NJ), North Carolina (NC), Ohio (OH), Texas (TX), and Utah (UT). The research team randomly selected six (6) of these states (UT, OH, GA, NC, MN, NJ) for a more comprehensive investigation of drone usage within their respective agencies.

To obtain the depth of understanding needed to satisfy the research objectives a personal interview with a subject matter expert (SME) with the agency would be necessary. An interview template was developed to help guide the interview process and provide a consistent approach for the interview of the SME with each state DOT. The template covered a broad spectrum of topics including UAS program initiation, current organization and logistics, a detailed review of drone usage, an investigation of the benefits of the operational deployment of UAS, the agency's involvement in drone technology and industry taskforces, and the agency's anticipated evolution of drone usage in the future.

The SME selected was the UAS champion (program coordinator) for each of the six state DOTs. This individual was identified and subsequently contacted to obtain their commitment to participation in the study. A time convenient for each interviewee was determined and prior to the interview, each individual was provided the interview template containing the topics of inquiry. Over the course of three weeks, the champion/program coordinator for all six state DOTs was interviewed for approximately one hour using an online video conference call application. With prior permission, all of the interviews were recorded to facilitate efficient use of the champion's time and ensure that their input was properly captured. Later, the interview recordings for each DOT were then categorized and encoded. To ensure an accurate summary of each champion's input they were subsequently provided a copy of the interview summary for their review and comment. The champions' comments and edits were then incorporated prior to the examination of the interview data.

1.3 Findings

The use of drones in the state DOT operations has gained traction over the past several years subsequent to the establishment of federal regulatory guidelines. The majority of the six DOTs that were interviewed started experimenting with drones only a few years ago in 2015 or 2016. However, Utah initiated operations in 2011 and Ohio started training in 2010-2012 and launched its first flight in 2013. When the six DOTs established their programs, the UAS tasks that were typically anticipated included monitoring construction and traffic, aerial photography, bridge inspection, surveying, and first responder operations. A primary reason for the initiation of their programs was to reduce cost, increase efficiency, and improve safety for both the agency and the public. During the development of their UAS program, most of the DOTs reached out to consultants, universities, and/or other DOTs for guidance. The state DOTs and universities that were mentioned included Utah State, Georgia Tech, and the DOTs in North Carolina, Oregon, Ohio, Utah, Delaware, Kansas, and Massachusetts.

1.3.1 UAS Current Uses

The current uses noted by each DOT are presented in table 1.5. All of the DOTs used drones for aerial photography which supports a broad spectrum of other uses including inspection, monitoring, surveying, and marketing/outreach activities. In addition, all of the DOTs were either investigating the use of drones or have currently deployed drones to supplement their bridge inspection program. Another common use identified by all of the DOTs was for communication and outreach activities. For example, the NCDOT has operationalized drones to assist with a variety of their communications needs including ribbon cuttings, public meetings, environmental programs, and construction updates.

Traffic monitoring was a use noted by five of the DOTs. Some of these DOTs had the capability to live stream data to their traffic operations center to assist with the management of high traffic flows, accident response, and disaster management. These same five states also utilized drones for as-built documentation of construction activities.

Surveying and mapping activities were being implemented by four DOTs. In addition, four states were using drones to aid with disaster management and/or to monitor avalanche, land, and rock slides. For example, the North Carolina DOT utilized drones to coordinate with the Highway Patrol and the Department of Public Safety to monitor conditions live as they unfolded after Hurricane Florence. Ohio, North Carolina and the New Jersey DOTs used drones to inspect and monitor rock falls and/or landslides that impacted their transportation infrastructure.

Table 1.5: Current DOT UAS uses.

Activity	UT	OH	GA	NC	MN	NJ	Total #
Aerial Photography	X	X	X	X	X	X	6
Bridge Inspection	X	X	X	X	X	X	6
Communication/Outreach	X	X	X	X	X	X	6
Traffic Monitoring	X	X	X	X		X	5
As-Built Documentation	X	X	X	X		X	5
Surveys/mapping	X	X			X	X	4
Avalanche/Land/Rock Slides	X	X		X		X	4
Disaster Management		X	X	X		X	4
Environmental	X			X		X	3
Quantity Surveys	X	X					2

Activity		UT	OH	GA	NC	MN	NJ	Total #
Accident Investigation		X			X			2
Safety Assessment					X			1
Utility & RR Inspection		X						1
	Total uses	11	10	6	10	4	9	

Only half the DOTS used drones for environmental investigation and assessment activities. Less common DOT operational uses for drones were for quantity surveys (volume calculations), accident investigation, safety assessment, and utility & railroad inspection.

The Utah DOT had the widest spectrum of drone usage followed closely by the DOTs in North Carolina, Ohio and New Jersey. The Minnesota and Georgia DOTs had operationalized a limited number of drone uses. These two states focused primarily on aerial photographs, bridge inspection, traffic monitoring, disaster management, and surveying/mapping.

Subsequent to the identification of the spectrum of drone use for each DOT the research team initiated a comprehensive investigation of two of the more technical and complicated applications for UAS – bridge inspection and surveying/mapping. Each DOT that had indicated drones were being used for one or both of these activities was probed to determine the extent that drones had been operationally deployed.

1.3.2 Bridge Inspection

All six of the DOTs had indicated drones were being used for bridge inspection activities. However, one-half of the DOTs were primarily in the testing and/or experimental stage. The remaining states that were performing some level of bridge inspection had initiated operations recently (UT-2016, GA-2017, OH-2018). The types of inspection that they were performing included documentation of deck delamination, thermal photography, and top/side inspection.

Even though the majority of the state DOT bridge inspection crews had access to drones for assistance with inspection activities the extent of drone use was limited. This was in large part due to the difficulty of drone flight underneath a bridge deck and the limitations of drones to provide tactile information. As a result, the inspection role for drones has been primarily to augment normal snooper truck bridge inspection activities.

Currently, the percentage of the state's bridge inspection program accomplished with drones is less than 10% in North Carolina, less than 5% in Minnesota, and less than 1% in New Jersey. The only state DOT that indicated wide drone usage was Utah. None of the state agencies have incorporated 3D modeling to support bridge inspection activities but five of the six DOTs expressed an interest in exploring the use of this technology.

UAS and associated technology currently do not have widespread application for bridge inspection. However, all of the six states except NJ intend to enhance and expand their use of drones in the agency's bridge inspection program. For example, Minnesota plans to grow its drone bridge inspection program 'exponentially'. Currently, they are formulating a drone bridge list that would include bridges that are more conducive to drone inspections such as high abutments, bridges over waterways, and bridges with limited access. Ohio recognizes that flying drones on and around bridges requires the highest level of skill because the drone is likely to be exposed to areas where GPS is deprived. Therefore, the agency is launching a new program called the 'drone deployment program' which is intended to train BIEs to cope with the challenges surrounding bridge inspection.

The primary reasons for state DOT interest in operational deployment of drones and associated technology are consistent from state-to-state. Even though only one of the states has actually analyzed the impact of using drones for bridge inspection the majority of state agencies expect drones to lower inspection costs, increase efficiency, speed up the inspection process, enhance quality, and improve pedestrian safety.

Several of the states subcontract a portion of their drone operations to third parties. Ohio noted that most of their contractors already use drones and Minnesota indicated that it would likely always utilize some third party contracts for drone operations. Minnesota noted that it has adopted this approach because drone technology advances at such a fast rate. As a result, the agency felt they needed consultant involvement and capabilities to keep abreast of trends/developments and to supplement their drone inspection activities.

1.3.3 Surveying and Mapping

The use of drone technology for survey and mapping by the DOTs sampled was more limited than for bridge inspection. Four states (UT, OH, MN, NJ) indicated some application(s) by their agency. NC was pilot testing drone use, and GA did not have any current or future plans to adopt this technology. The states indicating limited application were using drones to survey/map remote areas, for planning level missions, and/or perform volumetric calculations for earthwork. However, only one state agency (ODOT) was using drones to assist on a limited basis with the evaluation/validation of contractor payment applications. Two states (UT, NJ) have utilized drones for aerial imaging for initial roadway surveys. In addition, only one of the six states (UT) generated point clouds to assist in the production of surveys produced using drone technology.

The limited use of drones for surveying and mapping operations stemmed from industry and agency concerns regarding the accuracy of surveys relying on ‘drone technology’. The champion for the Ohio DOT noted that ‘surveyors do not trust the drone data for use beyond planning level needs’. Professionally licensed surveyors are reluctant to seal drone surveys.

To address this issue, two of the states (UT, NC) have conducted studies/tests to investigate the accuracy of drone surveying techniques. Utah found drones were most useful with softscapes where additional information about textures and water flows could be captured with a drone that is typically not recorded using traditional surveying practices. In their experience, accuracy depended on the quality of the data but it could be better than within one inch. However, Utah’s experience was that verification reports were essential for the validation of surface surveys produced using drone technologies. NCDOT performed photogrammetry testing and was unable to consistently meet accuracy requirements using only post-processed camera station positions. When the agency added ground control points they were able to achieve accurate results within 0.12’ to 0.18’.

1.3.4 Investigation of UAS Benefits

Each of the DOT champions was asked what their agency considered to be the chief advantage of incorporating drone technology into their operations. The feedback that was obtained from five of the six agencies is summarized in table 1.6.

Table 1.6: Chief advantages of UAS.

Chief Advantage(s)	UT	OH	NC	MN	NJ
Reduced cost	X	X	X	X	X
Reduced time		X	X	X	X
Improved quality of inspection	X				
Safer operations		X			X
Less impact on traffic		X	X		

All of those that reported felt that using drone technology reduced cost and a majority of the agencies thought that it also reduced the time it took to complete activities. Some agencies also felt it enhanced the quality of inspection activities, improved safety and lowered the impact that the agency's operations had on traffic flow.

Three of the agencies had investigated potential cost savings. Utah conducted a study with their state university and found a 60% savings with bridge inspections and a 50% savings with activities for deck delamination inspections. However, Utah did not find savings for other bridge inspection activities due to the FAA limitations/regulations. Minnesota found that the use of UAS for bridge inspection saved an average of 40%, in addition to eliminating the cost associated with traffic lane closures. New Jersey investigated the use of drones for high mast inspections and found that UAS increased efficiency and safety while at the same time reduced inspection cost.

1.4 Program Logistics

1.4.1 Drone Fleet

Most all of the state DOTs interviewed had a central group that managed their drone program with divisional control and management of the actual drone fleet. Maintenance of the agency's fleet of drones was most often handled by external third parties depending on the extent of work required.

The average size of an agency's drone fleet was seven (7) but ranged from three (3) for Utah to seventeen (17) for North Carolina. The majority of the drones used by the state DOTs were multirotor-copters (similar to a helicopter) with UT and OH reporting that they also used fixed-wing aircraft (similar to an airplane). Several drone manufacturers were mentioned in the interviews but the most commonly used drones were manufactured by DJI. Five of the DOTs owned at least one DJI Phantom series drone with DJI's M200, Inspire and Mavic series also commonly used. All of the responding agencies indicated that they intend to add to their fleet.

1.4.2 Pilots and Training

The number of licensed drone pilots within the agencies ranged from two for Minnesota to thirteen for Utah with an overall average of seven pilots. All of the responding agencies paid for the Part 107 pilot's exam but none of the agencies provided any financial incentive or another reward system for agency personnel receiving a pilot's license. Minnesota expressed that "Luckily, the excitement and interest outweighs the fact that we have no incentive" {for pilots}.

Pilot training beyond that required for the pilot's exam varied by the agency. Drone pilots for the Ohio DOT were responsible for their own licensing and training. The Utah DOT was currently developing a new training program that involved both practical and objective tests. Georgia presently had mandatory training on the agency's standard operating procedures and policies. Minnesota was in the midst of developing a formal training program for its pilots. Currently, MnDOT employees that wanted to be a pilot were required to take the Office of Aeronautics Ground Pilot school training and receive a 'sign off' from the school regarding their piloting capabilities in the field. Jew Jersey had one of the most comprehensive training programs. The agency has developed its own curriculum and training program covering three training phases: Phase 1 is Part 107 certification, Phase 2 is a practicum exam, and Phase 3 consists of hands-on training in the field. The entire training program takes 2 weeks.

1.4.3 Consultant Use

All of the state DOTs indicated that their consultants used drones for a variety of activities. Utah noted that their consultants have utilized drones for bridge inspection. In Georgia and North Carolina consultants utilized drones for project documentation. The champion for Minnesota DOT noted that consultants used drones for 'planning-level' surveys and disaster management whereas in New Jersey consultants use them for high mast inspection. The Ohio DOT champion noted that consultants used drones for everything that the state agency did, but more aggressively. Ohio also advised that consultant surveyors have embraced drones more enthusiastically than the agency.

Each of the state DOTs interviewed were asked what percentage of the agency's 'drone activities' were contracted to consultants. Georgia advised that almost all of their drone applications were performed in-house. Conversely, in Minnesota consultants were currently performing 90% of the DOT's drone activities. However, the agency indicated that they intended to lower the consultant percentage to 60% in the future. Utah and North Carolina also contracted a substantial portion of their work to consultants. Utah was currently contracting 60-75% and North Carolina was utilizing consultants for approximately half their drone activities.

1.4.4 Industry Involvement and Program Potential

The DOT champions that were interviewed for this study are also actively involved in UAS application, integration, and research activities with the Federal Highway Administration (FHWA), the National Association of State Aviation Officials (NASAO, and the Transportation Research Board (TRB)). The Utah drone champion serves on the FHWA UAV committee. Ohio's UAS program leader is a member of the FHWA EDC-5 committee, the TRB helicopter committee, and the geographic committee, and serves on the Ohio Attorney General's Committee on UAS. The North Carolina champion is the Vice Chair of the NASAO UAS Committee, a committee member of AV020 within TRB, a member of the UAS Subcommittee within the Aviation (AV) group of TRB, and a member of the FHWA EDC-5 UAS Integration team. Minnesota's leader also serves on the FHWA EDC-5 committee and the TRB Structure Maintenance Committee and the UAV champion for New Jersey serve on a subcommittee for NASAO. In addition to active involvement with the FHWA, NASAO, and TRB the champions regularly attended UAS conferences, participated in workgroups, and worked closely with other DOTs to stay abreast of rapidly changing UAS technology, operational applications, and emerging governmental regulations.

Looking forward, all of the DOTs forecast an expansion of their drone program with an increasing number of pilots, drones, and agency uses throughout the DOT. Over the next 5-10 years, the UAS champions predicted a larger role for drones in most categories/uses including traffic management, inspection, structural analysis, surveying, volume calculation, and communication.

New Jersey summarized the DOT's sentiment when the champion stated that the expanding role of drones would be 'significant'.

Prior to closing out the interview, each state DOT champion participating in this study was asked to identify other states they thought had advanced UAS programs (Note: none of the champions were aware of the other study participants). Collectively, a total of fourteen different states (NC, NJ, CO, MN, AL, UT, KY, IA, OH, DE, CA, MO, MA, GA) were identified by the champions. However, only five states were mentioned by three or more champions – Utah, Ohio, North Carolina, Minnesota, and New Jersey. All five of these states are DOT's participating in this study.

1.5 Summary

To investigate the degree to which drone technology has been incorporated into the daily operations of state transportation agencies the research team interviewed the 'drone champion' for each of six state DOTs that were identified as having a broad exposure to the spectrum of UAS uses. Each of these state champions had extensive involvement in the agency's drone program and was also actively involved in UAS application, integration, and research activities at the national level. In addition, during the interview process, five of the six states were identified as state DOTs with advanced UAS programs. The champions, along with their respective DOTs, are in many respects 'leaders' in the deployment of drone technology in state transportation agencies. The following conclusions are based on their input.

Drone Technology Adoption: The adoption of drone technology by state DOTs is in an 'early' stage. The six DOTs interviewed for this study all had experience with a wide range of drone activities. However, the program structure is rather 'loose' and the extent of operational deployment for most drone applications was limited. There are a number of factors that have contributed to the slow pace of adoption including: a) UAS are relatively new technology, b) federal guidelines/regulations for their use have only recently been established, c) equipment limitations, d) licensing and training requirements, and e) agency personnel resistance to change.

However, there is considerable interest in the deployment of drone technology. Agencies are optimistic regarding the favorable impact that drones could have on operational efficiency, cost, safety, and the traveling public. Agency expectations are high even with limited studies validating these anticipated outcomes. State DOTs plan to increase their drone fleet and pilot licensing/training to facilitate the expansion of their drone program.

Operational Deployment: Drone uses experiencing operational deployment have primarily been associated with 'video/camera' tasks such as aerial photography, traffic monitoring, communication and outreach, accident investigation, documentation, environmental assessment, and disaster management. For these applications, the drone is used primarily as an 'eye in the sky'. These uses require relatively simple equipment, technology and minimal pilot training which facilitates early operational deployment.

Drone applications that require more sophisticated, technologically advanced equipment, software, and pilot capabilities, such as bridge inspection and surveying, have experienced a slower pace of adoption. Equipment limitations, piloting capabilities, and federal requirements have retarded broad operational deployment of drones for bridge inspection. Technology, training, and industry resistance have restrained the use of drones for mapping, surveying, and volumetric calculations.

However, the forces of change are ever present and DOTs are planning to expand drone operations. One of the DOTs (MN) has been working with Intel to address some of the challenges with bridge inspection. Other DOTs are also investigating and/or deploying drone technology for certain bridge inspection activities. Similarly, to address industry resistance to the use of drones for mapping/surveying several DOTs and universities are investigating the accuracy of drone surveying techniques and volumetric calculations. The landscape for technology, equipment, and software for drone applications in the transportation sector is changing rapidly. New Jersey's champion advised that demand from operating divisions would fuel program expansion and he forecast that "Soon, drone use will be as common as mobile phones."

CHAPTER 2

Literature Review

2.1 Introduction

The use of UAS has significantly increased over the past 3 years in the United States. In August of 2016, the FAA released Title 14 Part 107 of the Code of Federal Regulations which removed much of the regulatory limitations on the use of UAS for commercial applications (FAA, 2018b). There are many applications for drones that are currently being explored. Some of the applications that have shown promise in the literature are bridge inspections (Gillins, Parrish, Gillins and Simpson, 2018; Otero, Gagliardo, Huang and Cosentino, 2015), construction safety monitoring (Gheisari, Irizarry and Walker, 2014), disaster management (Adams, Levitan and Friedland, 2014), and construction progress monitoring (Lin, Han, and Golparvar-Fard, 2015) just to name a few. The World Road Association (WRA) conducted a comprehensive international study of how UAS can be leveraged to improve roadway design, construction, and maintenance (2017). In their report, they recommended four primary areas that could benefit from UAS technology. The four areas include bridge inspection, automated asphalt pavement inspection, asset inventory and maintenance and pre-construction surveys. Their recommendation of leveraging UAS to improve pre-construction surveys was the genesis of this study. As-built conditions of future roadway projects are commonly obtained by aerial imagery captured by manned aircraft. The WRA report indicates that “Using a survey grade UAS with RTK GPS and Red Green Blue (RGB) imaging capabilities can be a very good alternative to traditional methods” (World Road Association, 2017). The report defines “survey grade UAS” as one with geo-referenced, high-resolution imagery that can create a point cloud within 3cm (0.098 feet) accuracy. The objective of this study is to see if commercially available, off-the-shelf UAS (i.e. which are not necessarily “survey grade”) and software can be used to create surveys that are within these tolerances and be a benefit to the South Carolina Department of Transportation.

2.2 Title 14 Part 107

Part 107 opens the airspace for most commercial drone use cases but does provide requirements and limitations. One of the requirements is that the drone operator must hold an FAA remote pilot certificate. The certificate is earned by passing a two-hour knowledge test that covers sectional charts, airport operations, Part 107 rules, weather and a host of other topics. The exam does not have a practical component and demonstrating competence flying an aircraft is not required. Some of the restrictions placed on flying drones include operating during daylight hours, not flying over people, flying in Class G airspace or receiving air traffic control authorization, maintaining line of sight with the aircraft, register the drone with the FAA and reporting damage caused by the drone in excess of $500 (FAA, 2018b). The FAA will grant waivers to some of these restrictions if the risk associated with the mission(s) has been properly mitigated with alternative methods.

With the technology commercialize and much of the regulations removed, drone use in the United States has significantly grown. As of the middle of 2018, 100,000 remote pilot certificates have been issued by the FAA (FAA, 2018c). Based on current trends, the FAA projects that there will be 450,000 registered commercial drones by 2022 (FAA, 2018a). Many construction companies are used drones for surveying, construction site inspections, safety inspections, project reports, marketing, live feed/virtual tours, site logistics, BIM models, thermal imaging and quantity take-offs (Ayemba, 2019). This last use case is the focus of this paper. Many contractors and state departments of transportation are using drones as a tool to calculate stockpile and earthwork volumes. Images captured with the drones processed through commercially available software can create point clouds significantly denser than conventional survey methods at a fraction of the time. The question that remains and will be addressed in this paper is "how accurate are the volume calculations." This paper provides the results of a structured experiment where a large cardboard pyramid with a known volume is used to evaluate the accuracy of surveys created from drone missions with different parameters. The experiment is then continued in an active state DOT borrow pit where the drone-based calculations are compared to the volumes computed by a professional land surveyor licensed with the state.

2.3 Background

The use of UAS for geomatics applications is not a new concept. Military surveillance and reconnaissance applications were being explored as early as the 1970s (Przybilla and Wester-Ebbinghaus, 1979). However, what is now thought of as modern UAS photogrammetry really began in the early 2000s (Colomina, Blázquez, Molina, Parés and Wis, 2008; Colomina and Molina, 2014; Eisenbeiss, 2008). Driving the increased use of UAS for surveying and mapping was the development of low-cost platforms and cameras coupled with improved GNSS/INSS for precision drone navigation (Remondino, Barazzetti, Nex, Scaioni, and Sarazzi, 2011). Because of the speed at which new technology is driving this field, past studies remain relevant for only a short period of time and current technology is not extensively tested (Hugenholtz, Walker, Brown, and Myshak, 2014; Siebert and Teizer, 2014). However, several recent studies have been conducted which show the potential of using drones for pre-construction surveys. One example was a study conducted by Hugenholts et al. where an Aeryon Scout drone with a Photo 3S high-resolution camera was used to capture georeferenced images of a stockpile of gravel. The models created had a resolution of 3.5cm (0.115 feet) with an RMS error of .097m (0.003 feet). The drone-based volumetric calculation was within 2.55% of actuals. Siebert and Teizer showed similar results in their study where they surveyed an open testbed and had errors of 0.6cm (0.020 feet) in the horizontal direction and -1.1cm (-0.036 feet) in the vertical direction (2014). Lucieer, de Jong, and Turner used an OktoKopter equipped with a Canon 55D DSLR camera to monitor landslides in their 2014 study. In their experiments, they found a horizontal accuracy of 7cm (0.230 feet) and a vertical accuracy of 6cm (0.200 feet) (2014). The most comprehensive study on the accuracy of drone-based surveys found in the literature was conducted by Aguera-Vega, Carvajal-Ramirez and Martinez-Carricondo in 2017. Aguera-Vega et al studied the influence of altitude, terrain morphology and the number of ground control points on digital surface model accuracy. The study compared 60 photogrammetric models considering five terrains, four flight altitudes and a varying number of ground control points. The RGB camera used was a Sony Nex 7 mounted under a MikroKopter drone (Moormerland, Germany). They found that the most accurate combination of flight altitude and the number of ground control points was 50 m (164 feet) and 10 GCPs which led to an accuracy of 0.053m (0.17 feet) horizontally and 0.079m (0.26 feet) vertically. Each of these studies used commercially available technology and support the WRA report's recommendation that drone-based surveys can be used for preconstruction surveys.

2.4 Photogrammetry and Factors Influencing Accuracy

The term photogrammetry is loosely defined as the practice of using photographs in surveying or mapping to measure distances. The images can come from any number of sources but are increasingly being captured with small UAS. The images are then stitched together with software to create point clouds, 3D meshes and reality models. This "stitching" is referred to as "structure from motion" (SfM) in the photometric discipline. The stitching of images from SfM software is accomplished through "aerial triangulation." Aerial triangulation calibrates and orients cameras to extract unique features identified in several images that are converted to geospatially located points (Remondino et al., 2011). The SfM outputs are then used to calculate distances, volumes, and topography or to support a host of other workflows. As UAS technology has become accessible to commercial users, so has the photogrammetric software. ContextCapture, Pix4D and PhotoScan are several examples of desktop SfM applications but other web-based platforms such as DroneDeploy are also readily available to consumers. Despite the availability of the hardware and software, high-quality photometric surveys remain as much of an art as a science particularly when it comes to data acquisition. Several key terms and concepts will be addressed before the results of the study are discussed.

2.4.1 Average Ground Resolution

SfM photogrammetry uses 2D images to create 3D outputs (Snavely, Seitz, and Szeliski, 2007). A single image is essentially a 2D plane with millions upon millions of small colored points called "pixels." Camera quality is often measured by the number of megapixels it can capture. A single megapixel is nominally 1-million pixels per square inch. Many cell phones come equipped with a 12-megapixel camera meaning the images they capture contain 12-million pixels per square inch. The color of the pixel is typically limited to red, green or blue, commonly referred to as an "RGB" image. Other colors are perceived as the human eye blurs combinations of RGB pixels in various combinations. Images with equal combinations of red and blue pixels would appear purple. However, for photometric surveying, what is more important than color is the size of the land surface that one pixel represents. For a low megapixel camera taken from a high altitude, the size of one pixel could be greater than a meter whereas a high-quality camera at a low altitude could be sub-centimeters or even sub-millimeter. There are several terms used to express this such as "ground sampling distance" or "ground resolution." This study used Bentley's ContextCapture as its SfM software which uses the term "Average Ground Resolution" (AGR), so that will be used in this paper as well.

2.5 Estimation of Accuracy of Drone Based Surveys

While there are several SfM photogrammetry software packages available, they all follow a similar workflow and have internal diagnostics to gauge the accuracy of their outputs. The first is the size of the "dataset." The dataset is the images that have been calibrated and positioned so they can be included with the reconstruction model. From the dataset, "keypoints" are automatically detected by the SfM software. Keypoints are 2D points of interest identified in an individual image. Surfaces with high contrasting features will have more keypoints than a surface like snow or sand with fewer points that can be identified as unique. The software then matches 2D keypoints from two or more images to triangulate a 3D "tie point." The more tie points the denser the point cloud created. A diagnostic tool used by photogrammetrists is the number of images with unique keypoints used to triangulate the tie points. There is less certainty of the true location of a tie point created with two keypoints then with seven. In the researchers' experience, it is not uncommon for a three hectare survey to have 350,000 keypoints used to create 15,000 tie points. Depending on the terrain, it is often useful to create manual tie points where the user identifies the same point in space in multiple images. This can assist the software in syncing dataset blocks together that it was not able to do with the auto aerial triangulation process.

Another tool used to measure the accuracy of the model is the "reprojection error" or RMSE. The RMSE is commonly defined by the pixel and is the root mean square value of errors for each tie point. As the unit of measure for the RMSE is the pixel, to understand the level of error in real world units you would multiply the RMSE (error in pixels) by the AGR (size of one pixel).

2.5.1 Ground Control Points and Checkpoints

Most commercial grade drones come with an internal GPS and can imprint a geospatial coordinate with the images it captures (Remondino et al., 2011). The accuracy of the GPS sensor varies but is commonly within a meter (Buczkowski, 2017). Having georeferenced images is not required to create the photometric models although it significantly reduces computing time. Models created with images with commercial grade GPS coordinates may have a high internal relative accuracy. Internal relative accuracy is defined as accuracy within the model only. For absolute accuracy, meaning that the model is accurately located in the real world, ground control points (GCPs) are needed. GCPs are points within the model with known geospatial coordinates typically measured by a surveyor. The photogrammetrists will identify the GCP in at least two images and the SfM software will then fit the model around them. A useful analogy is that the model created is a sheet of rubber and the GCPs are pins. The model is stretched and compressed to fit around known points in the real world. Understanding how well the "rubber fits" is another important diagnostic that will be discussed in the results section. However, perhaps the clearest diagnostic tools for drone-based surveys are "checkpoints." Checkpoints also have known coordinates but are not used to calibrate the model parameters, rather they are used to directly compare the computed location of a point with the real-world location of that same point. The accuracy of checkpoints will be a fundamental measure for this study.

2.6 Estimation of Accuracy of Drone Based Stockpile Volume Calculations

The use of UAS for geomatics applications is not a new concept. Military surveillance and reconnaissance applications were being explored as early as the 1970s (Przybilla and Wester-Ebbinghaus, 1979). However, what is now thought of as modern UAS photogrammetry really began in the early 2000s (Colomina, Blázquez, Molina, Parés and Wis, 2008; Colomina and Molina, 2014; Eisenbeiss, 2008). Driving the increased use of UAS for surveying and mapping was the development of low-cost platforms and cameras coupled with improved GNSS/INSS for precision drone navigation (Remondino et al., 2011). Because of the speed at which new technology is driving this field, past studies remain relevant for only a short period of time and current technology is not extensively tested (Hugenholtz, Walker, Brown, and Myshak, 2014; Siebert and Teizer, 2014). However, several recent studies have been conducted showing the potential of using drones for pre-construction surveys. One example was a study conducted by Hugenholts et al. where an Aeryon Scout drone with a Photo 3S high-resolution camera was used to capture georeferenced images of a stockpile of gravel (2014). The models created had a resolution of 0.11 feet with an RMS error of 0.003 feet. The drone-based volumetric calculation was within 2.55% of actual. Siebert and Teizer showed similar results in their study where they surveyed an open testbed and had errors of 0.020 feet in the horizontal direction and -0.036 feet in the vertical direction (2014). Lucieer, de Jong, and Turner used an OktoKopter equipped with a Canon 55D DSLR camera to monitor landslides in their 2014 study. In their experiments, they found a horizontal accuracy of 0.230 feet and a vertical accuracy of 0.200 feet (2014). The most comprehensive study on the accuracy of drone-based surveys found in the literature was conducted by Aguera-Vega, Carvajal-Ramirez and Martinez-Carricondo in 2017. Aguera-Vega et al. studied the influence of altitude, terrain morphology and the number of ground control points on digital surface model accuracy. The study compared 60 photogrammetric models considering five terrains, four flight altitudes and a varying number of ground control points. The RGB camera used was a Sony Nex 7 mounted under a MikroKopter drone (Moormerland, Germany). They found that the most accurate combination of fight altitude and the number of ground control points was 164 feet and 10 ground control points which lead to an accuracy of 0.17 feet horizontally and 0.26 feet vertically. Each of these studies used commercially available technology and support the position that drone-based models can be used for preconstruction surveys and determine stockpile volume.

2.7 Opportunity for UAS to Support Bridge Inspection

Another civilian use case for UAS is bridge inspections. The FHWA authors the Bridge Inspector's Reference Manual (BIRM), which provides the standard for bridge inspections (Ryan, Hartle, Mann, and Danovich, 2012). Bridges are most commonly inspected visually involving walking on decks, using binoculars to observe points of interest or using an under bridge inspection truck (UBIT) for difficult to reach places (Dorafshan and Maguire, 2018). UBITs require skilled and qualified operators (Zink and Lovelace, 2015) and can be difficult to schedule as there are generally only a limited number of them in any given district (Dorafshan and Maguire, 2018). Other issues with UBIT include congesting traffic, added weight to bridges, and endangering inspectors and the traveling public. The indirect cost of using UBIT can exceed the direct cost of the inspection making alternative methods very desirable (Dorafshan and Maguire, 2018). One such alternative is UAS and several state DOT have started researching their use to support bridge inspections.

2.7.1 Past Evaluations of UAS Supporting Bridge Inspections

Gillins, Parrish, Gillins, and Simpson conducted a comprehensive review of the formal UAS DOT research project as part of a sponsored research project by the Oregon DOT (ODOT) and the FHWA (2018). They found that multiple states have made significant strides in testing UAS to support their agency's mission. For example, Arkansas DOT was one of the first DOT's to study drones for collecting traffic data but that the regulations of the time were too burdensome for practical application (Frierson, 2013). The study was conducted 3-years prior to Title 14 Part 107's adoptions removing many of those restrictions. The Connecticut DOT (CDOT) experimented with a small multi-rotor UAS to photo-document the Gold Star Bridge over the Thames River in 2016 (Statcom, 2016). CDOT found that they were able to document the bridge with aerial photographs in 30-minutes which would have normally taken several hours using UBIT and climbing equipment. The FDOT collaborated with the Florida Institute of Technology to evaluate if drone-captured images compared with images collected during conventional inspections (Otero, Gagliardo, Dalli, Huang, and Cosentino, 2015). They used several bridges and high mast luminaires to conduct their testing. They found that the two photo groups were largely comparable but that there were still gaps in the drone data that should be explored further in the future. Similarly, to the FDOT, the Michigan DOT (MDOT) also evaluated drones for bridge inspections but expanded their study to traffic monitoring as well (Brooks, Dobson, Banach, Dean, Oommen, Wolf, Havens, Ahlborn, and Hart, 2015). In the Brooks et al., study, they evaluated five drone platform systems with a variety of sensors including optical, LIDAR and thermal. The findings were very supportive of the technology. Minnesota DOT (MnDOT) contracted with Collins Engineers to conduct a multi-phase evaluation of drone supplement bridge inspections (Lovelace, 2015). Their initial results were very favorable so the study was expanded to include bridges with a variety of structures including steel through arch, steel high truss, corrugated steel culvert and movable steel truss (Wells and Lovelace, 2017). The expanded study was also very positive noting that augmenting an inspection with a UAS could provide a cost savings of as much as 66%. ODOT also evaluated the potential of using drones as a cost-saving tool with their inspections. They used a UAS to conduct a structural inspection of six bridges and three communication towers and found a benefit-cost ratio of 9 and an estimated average cost savings of $10,000 per bridge (Gillins et al., 2018).

The FHWA has taken notice of this trend. In a publication by FHWA's Center for Accelerating Innovation, they note that "construction inspectors that use UAS are reducing inspection time, improving effectiveness, increasing safety, and lowering costs" (FHWA, 2019). The center has also financial supported states wishing to deploy the technology through several research initiatives including the State Transportation Innovation Council (STIC) incentive program, Accelerated Innovation Deployment program and the Accelerating Market Readiness program (Center for Accelerating Innovation, 2019).

CHAPTER 3
Structured Evaluation of a UAS Based Land Survey

3.1 Methodology

The central goal of this study is to address the question of how accurate drone-based surveys are given real-world conditions and commercially available equipment. To address this question a structured experiment was created using a 14,000m2 (3.5 acres) site. The test site was made up of two large fields adjacent to one another. The field to the north was approximately 2.1m (7 feet) lower than the south field. Thirty-one, 30.5cm (1.000 feet) x 30.5cm (1.000 feet), black and white aerial targets were distributed evenly across both fields. The aerial targets were located by a licensed professional land surveyor using a robotic total station. Sixteen of the aerial targets were used as GCPs and the other 15 were used as checkpoints. Figure 3.1 shows the two fields and distribution of GCPs and checkpoints.

Figure 3.1: Test field with ground control points and checkpoints.

DJI is the leading drone manufacturer commanding 74% of the global commercial UAS market (Skylogic Research 2018). Two commercially available and commonly used DJI aircraft were selected for this experiment. The first UAS was DJI's Phantom 4 Pro (P4P). The P4P comes with a 1" complementary metal-oxide-semiconductor (CMOS), a 20-megapixel camera located on a 3-axis stabilized gimbal under the hull. The second aircraft was a DJI M210RTK with a Zenmuse X5 camera (M210-X5). The X5 is a 4/3 CMOS, 16-megapixel camera. It is also mounted on a stabilized gimbal facing downward.

Eighteen waypoint-assisted missions were preprogrammed using the Pix4D Capture app. The missions for both aircraft were identical in altitude and image overlap (80%). The three altitudes selected for the experiment were 13m (40 feet), 38m (125 feet), and 107m (350 feet) from the low field (altitude was approximately 2m (7 feet) less from the south field). The 13m (40 feet) altitude was selected as it was the lowest reasonable altitude to capture the data. It was assumed that these images would create the most accurate surveys as they would have the smallest AGR. In the United States, the FAA limits the altitude of UAS to 122m (400 feet). The 107m (350 feet) altitude was selected as it was just under this ceiling. The data would be useful for pilots who wanted to fly as high as possible with a reasonable safety factor. It was assumed that the images captured at this altitude would provide the low-end range of expected survey accuracy. The altitude of 38m (125 feet) was selected to be a midrange between the two other altitudes. Three identical missions at each of the three altitudes were flown by both aircraft to determine the level of variance in the surveys given images captured at different times. The experiment was conducted on a cloudless day, minimizing the effect that varying lighting conditions would have on the surveys. The effect of shadows did not play a major factor in the experiment, as the aerial targets were flat, did not cast a shadow, and received direct light at all times.

Over the 18 missions, nearly 3,500 nadirs (downward-facing) images were collected. A single survey mission of the site at 13m (40 feet) resulted in 587 images taken over approximately an 18-minute time period. The images were input into Bentley's ContextCapture SfM software along with the GCP coordinates from the professional land surveyors. The researchers then manually located the center point of the aerial targets which corresponds to the true coordinates. The software requires the CGP coordinate to be identified in at least three images; however, for this experiment, the researchers located them in five images. Half of the targets were used as GCP (odd numbers of targets 1 – 31) and the other half used as checkpoints (even numbers of targets 2-30).

3.2 Results

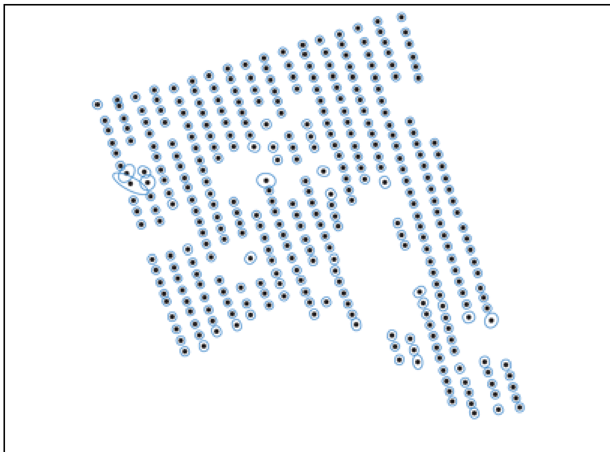
This section will discuss the accuracy of the photometric surveys. The findings have been broken down into two main areas. The first will deal with the overall accuracies of the drone-based surveys by altitude and aircraft. Each of the altitudes was flown three times and the accuracy of the checkpoints will be averaged together. In the second section, deviations observed between the missions flown at the same altitude will be discussed.

3.3 Overall Accuracy of a Drone Based Survey

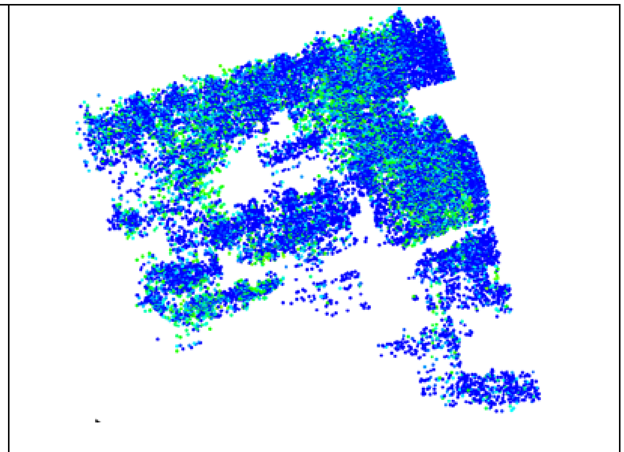
In this section of the paper, the overall accuracy of the models created from all flights and aircraft will be reviewed. Table 3.1 shows the internal diagnostics used to estimate the accuracy of the survey. The three identical flights at 12m, 38m and 107m are averaged together in this table but will be analyzed separately later in the paper. The AGR ranges between 1.78mm (0.006 feet) (M210-X5 at 13m) and 27.67mm (0.009 feet) (P4P at 107m). The AGR increases as the altitude increases as one would expect and values between the two aircraft are similar. The RMSE for each tie point is measured by the number of pixels, and generally, a value less than 1 pixel is considered to have high accuracy, 1 – 3 pixels is the medium level of accuracy, and anything greater than 3 pixels are considered to have a low level of accuracy (Bentley 2019). The study findings show that the RMSE are all lower than 2 pixels with the P4P outperforming whereas the M210-X5 RMSE was .88, 1.43 and 156 pixels. The size of the pixel (AGR) multiplied by the RMSE gives you the error in real-world units. However, the RMSE is misleading in table 3.1 when it comes to the 13m (40 feet) missions. While an RMSE of 0.88 and 0.60 pixels from the M210-X5 and P4P respectively is generally considered a high-quality model, notice that only 47% and 56% of the image dataset was able to be processed by the software. Figure 3.2 compares the data acquisition for the P4P at 13m (40 feet) and 38m (125 feet). Image A in figure 3.2 shows the camera position uncertainty of each image. The black dot represents the computed location of the camera and the blue circle is the location uncertainty. Notice that a large section of the bottom of the image which is over the high (south) field is missing. This loss of data is shown in Image B of figure 3.2 as well. Image B shows the tie points used to create the model. Many of the tie points over the south field are lost and the density of tie points is significantly thinned over the upper middle (low field). The loss of data was not seen with the higher-altitude flights. Table 3.1 shows that 98% or more of the images were used in the reconstructions from images at 38m (125 feet) and 107m (350 feet) from both aircraft. Image C and D from figure 3.2 shows a uniform pattern of where the drone was located when it captured calibrated images and a more consistent density of tie points. The researchers believe that at the low altitudes, there were insufficient distinguishing features in the open grass field for the software to create enough tie points to triangulate the images. This is supported in table 3.1 by the significantly fewer tie points per photo at 13m (40 feet) compared to flights at 38m (125 feet) and 107m (350 feet).

Table 3.1: Estimated accuracy of drone-based surveys.

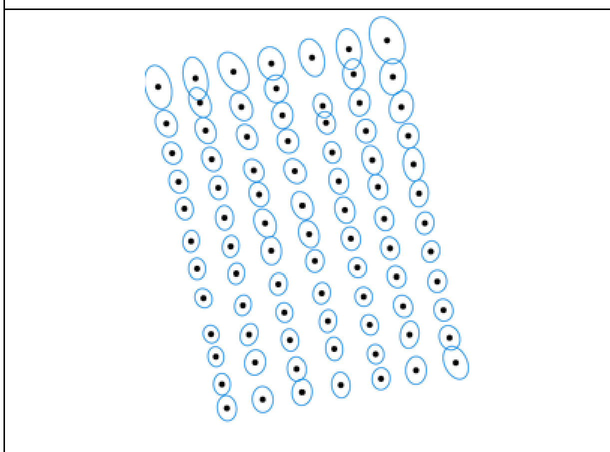
Aircraft	Altitude [meter]	Average Ground Resolution [mm]	Dataset %	Median Tie Points per photo	RMSE [pixels]	Average AGR Reprojection Error [mm]
M210-X5	13	1.78	47%	135.67	0.88	1.57
	38	8.17	98%	838.33	1.43	11.71
	107	23.61	99%	646.33	1.56	36.76
P4P	13	1.93	56%	243.67	0.60	1.16
	38	9.37	100%	1331.67	0.87	8.16
	107	27.67	100%	771.33	1.21	33.48



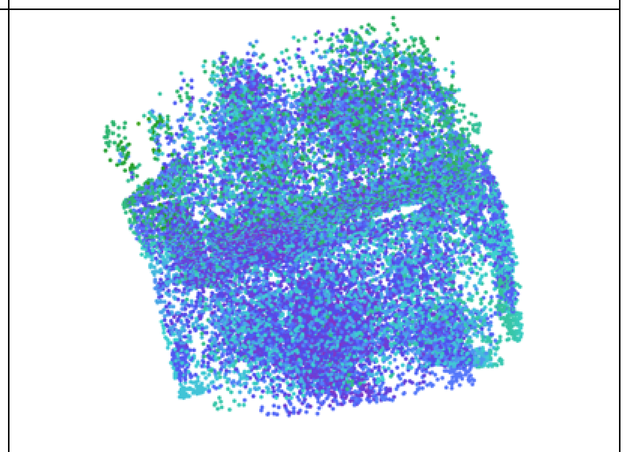
A) Camera Position Uncertainties at 13m (40')



B) RMSEs per Tie Point (40')



C) Camera Position Uncertainties at 38m (125')



D) RMSEs per Tie Point (125')

Figure 3.2: Data acquisition of P4P-A at 13m and 38m.

3.3.1 Fitness of Ground Control Points

When evaluating the quality of a model, a useful diagnostic tool is to compare the distance from the computed GPCs location to the true surveyed coordinate. Table 3.2 shows this comparison by indicating the median 3D error. This is the median error distance in the XYZ plane of the 16 GCPs. It should be noted that only 42% of the GCP from the M210-X5 and 10% of the P4P could be computed from the 13m (40 feet) flight and that care should be taken before making an assumption of the quality of those models. The computed GCP locations for the two aircraft are consistent for the altitudes. The computed GCP locations for the P4P 38m (125 feet) and 107m (350 feet) models were 1.21cm (0.040 feet) and 2.81cm (0.092 feet) from actual respectively. The M210-X5 was roughly twice this at 4.00cm (0.131 feet) and 4.60cm (0.151 feet) at 38m (125 feet) and 107m (350 feet). It is important to note that this exercise is a good diagnostic tool of the model but does not gauge real-world accuracy. The SfM software uses the GCP to build the model so it would not be good practice to then use those same points to gauge the accuracy of computed points in the model. The best tool to gauge the true accuracy of the model is the comparison of checkpoints which will be discussed in the next section.

Table 3.2: Comparison of computed GCP to geolocated GCP.

Aircraft	Altitude [meter]	Calculated GCP	Median 3D Error [cm]
M210-X5	13	42%	1.23
	38	100%	4.00
	107	100%	4.60
P4P	13	10%	5.78
	38	100%	1.21
	107	100%	2.81

3.3.2 Checkpoint Accuracy

Fifteen geolocated aerial targets were used as checkpoints to evaluate the survey accuracy. Table 3.3 shows the accuracy of the three identical flights averaged at the three altitudes. As discussed earlier, the 13m (40 feet) models were not well reconstructed. Approximately a third of the checkpoints could not be reconstructed, so the results from this altitude will be ignored as little meaningful results can be gleaned. However, at the 38m (125 feet) and 107m (350 feet), all of the checkpoints were reconstructed. In this experiment, the researchers manually identified the GPCs and checkpoints in five images. The "median" RMS is the median value of the 15 checkpoints. The RMSE for the M210-X5 was 7.19 and 3.18 pixels which generally indicates a low-quality model. The models for the P4P were 2.07 and 1.29 for altitudes of 38m (125 feet) and 107m (350 feet) respectively. A lower RMSE (better) at higher altitudes further demonstrates that a limited number of distinguishing features in the images reduced the quality of the models produced.

Table 3.3: Checkpoint accuracy of three altitudes.

Aircraft	Altitude [meter]	Calculated CP	Median RMSE [pixels]	Median 3D Error [cm]	Median Horizontal Error [cm]	Median Vertical Error [cm]	RMSE * AGR [cm]
M210-X5	13	69%	231.74	94.56	36.58	-33.88	41.24
	38	100%	7.19	5.67	4.15	-0.53	5.88
	107	100%	3.18	7.64	3.70	-1.42	7.51
P4P	13	71%	1163.52	567.92	447.64	178.02	224.56
	38	100%	2.07	1.90	0.82	-0.14	1.94
	107	100%	1.29	3.26	1.73	-0.17	3.56

The median 3D error, horizontal error and vertical error shown in table 3.3 indicate the distance between the computed checkpoint location and the known geolocated position. The 3D error is the distance from actual in the XYZ plane. Horizontal error and vertical error are components of the 3D error where the horizontal error is in the XY plane (earth's surface) and the vertical error is only in the Z plane (elevation). It can be seen here that the P4P outperformed the M210-X5 in overall accuracy. At 38m (125 feet), the P4P averaged a 3D error of 1.90cm (0.062 feet) whereas the M210-X5 error was 5.67cm (0.186 feet). With most surveys, traditional and drone-based, the horizontal error is typically less than the vertical error. Of the 18 survey missions, in only five was the median vertical error greater than the horizontal error. This is further evidence of the significant impact a site with relatively few unique features has on survey accuracy.

Another way of evaluating the accuracy of the model is by reviewing the RMSE (root mean square error). The values shown are the checkpoints reprojection errors in all photos that see it. The RMSE (measured in pixels) multiplied by the AGR (size of a single-pixel) put the RMSE into real-world units. We see in table 3.3 that the computed RMSE and the median 3D error are nearly the same (excluding the 13m flight).

3.4 Deviation between Flights

In this study, three missions with identical flight parameters were performed at each altitude to assess variability in the resulting models. The images were captured during a cloudless day without any appreciable wind removing shading or significant movement in the grass as an influencing factor. Table 3.4 shows the results of the internal accuracy estimates of the models. The AGR did not change significantly and as expected scaled larger with the higher altitudes. The largest deviation was with the P4P at 38m (125 feet) and had a range of 0.46mm (4.9% of average). The researchers found it surprising that there was so much of a difference in the number of tie points computed per photo. The number of tie points relates to how strongly the images can be stitched together into a 3D reconstruction. In the experiment, the percent deviation (range divided by average) spanned from 22.7% in the 38m (40 feet) P4P flights to 68.5% with the 107m (350 feet) P4P flights. Specifically, flight P4P-107C has over twice the number of tie points (1,101 tie points) as flight P4P-107A (573 tie points) even though the data was collected with identical flight parameters and all other environmental factors controlled for. Despite the fluctuation in tie points, the RMSE was fairly consistent. The highest difference from average was the M210-X5, flight 107C which had 0.16 pixels of RMSE greater than the average of 107A, B, and C. Given that an RMSE of 1 pixel is considered a high-quality model, a deviation of 0.16 pixels is relatively inconsequential.

Table 3.4: Variability of internal accuracy estimates between flight missions with identical flight parameters.

Aircraft	Altitude [meters]	Average Ground Resolution		Median Tie Points per photo		RMSE	
		mm	Difference from Average	No.	Difference from Average	Pixels	Difference from Average
M210-X5	38A	8.22	0.05	983	144.67	1.50	0.07
	38B	8.12	-0.05	749	-89.33	1.34	-0.09
	38C	8.17	0.00	783	-55.33	1.46	0.03
	% Deviation	1.2%		27.9%		11.2%	
	Range	0.10		234.00		0.16	
	107A	23.69	0.08	806	159.67	1.52	-0.04
	107B	23.42	-0.19	495	-151.33	1.43	-0.13
	107C	23.73	0.11	638	-8.33	1.72	0.16
	% Deviation	1.3%		48.1%		18.6%	
	Range	0.30		311.00		0.29	
P4P	38A	9.12	-0.25	1182	-149.67	0.87	0.00
	38B	9.42	0.04	1329	-2.67	0.86	-0.01
	38C	9.59	0.21	1484	152.33	0.88	0.01
	% Deviation	4.9%		22.7%		2.3%	

Aircraft	Altitude [meters]	Average Ground Resolution		Median Tie Points per photo		RMSE	
		mm	Difference from Average	No.	Difference from Average	Pixels	Difference from Average
	Range	0.46		302.00		0.02	
	107A	27.22	-0.45	573	-198.33	1.15	-0.06
	107B	27.76	0.09	640	-131.33	1.14	-0.07
	107C	28.03	0.36	1101	329.67	1.34	0.13
	% Deviation	2.9%		68.5%		16.5%	
	Range	0.80		528.00		0.20	

While the internal diagnostics are useful, the variation in the checkpoints is a better means of gauging accuracy. Table 3.5 shows the variability of the checkpoints for both aircraft at 38m (125 feet) and 107m (350 feet). It can be seen that the M210 with the X5 camera had significantly more variability in its models' checkpoint RMSE than the P4P. The RMSE for the M210-X5 ranged 2.25 pixels (the difference between 5.95 and 8.20 pixels) at 38m (125 feet); however, it was only .14 pixels for the P4P at the same altitude. A similar comparison was found at the 107m (350 feet) altitude as well. It was shown in table 3.3 that the P4P had higher accuracy than the M210-X5, as demonstrated with a 3D error of the checkpoints of 1.9cm (0.062 feet) compared to 5.67 cm (0.186 feet) at 38m (125 feet) and 3.26cm (0.107 feet) compared to 7.64cm (0.251 feet) at 107m (350 feet). Table 3.5 shows that there is variability between both of the M210-X5 flights and the higher altitude P4P flight, however the 38m (125 feet) P4P had fairly consistent checkpoint accuracies with a range of 0.75cm (0.025 feet), 0.23cm (0.008 feet) and 1.27cm (0.042 feet) in the median 3D, horizontal and vertical errors respectively. The median 3D error for the three surveys was 1.46cm (0.048 feet), 2.02cm (0.066 feet) and 2.22cm (0.073 feet) (average of 1.9cm (0.062 feet)) which is a range of 0.75cm (0.025 feet). The deviation seen here was likely caused by slight differences in the images and human error. While the preprogrammed flight paths were identical, the images were captured at slightly different positions horizontally and vertically due to discrepancies in the GPS-based navigation and other environmental factors such as wind. Additionally, the researchers manually locate the GCPs and checkpoints in five images each. The researchers made a good faith effort to locate them as accurately as possible. However, at high magnification, the pictures are pixelated and knowing which pixel is the exact center of the aerial target is a judgment call.

Table 3.5: Variability of checkpoint accuracy between flight missions with identical flight parameters.

Aircraft	Altitude [m]	Median RMSE		Median 3D Error		Median Horizontal Error		Median Vertical Error	
		Pixels	Difference from Average	cm	Difference from Average	cm	Difference from Average	cm	Difference from Average
M210-X5	38A	7.42	0.23	8.02	2.35	4.71	0.56	-2.83	-2.30
	38B	8.20	1.01	4.91	-0.76	4.13	-0.02	0.28	0.81
	38C	5.95	-1.24	4.08	-1.59	3.61	-0.54	0.96	1.49
	Range	2.25/31.3%		3.94		1.10		3.79	
	107A	3.32	0.14	7.81	0.17	3.86	0.16	-4.35	-2.93
	107B	2.82	-0.36	7.66	0.02	4.25	0.55	-0.66	0.76
	107C	3.4	0.22	7.44	-0.20	3.00	-0.70	0.74	2.16
	Range	0.58/18.2%		0.37		1.25		5.09	
P4P	38A	2.14	0.07	2.22	0.32	0.91	0.09	-0.81	-0.66
	38B	2.00	-0.07	1.46	-0.44	0.68	-0.14	0.47	0.61
	38C	2.06	-0.01	2.02	0.12	0.88	0.06	-0.09	0.05
	Range	0.14/6.8%		0.75		0.23		1.27	
	107A	1.09	-0.20	2.68	-0.58	1.61	-0.12	1.17	1.34
	107B	1.32	0.03	2.73	-0.53	1.85	0.12	0.54	0.71
	107C	1.45	0.16	4.37	1.11	1.73	0.00	-2.22	-2.05
	Range	0.36/28.0%		1.69		0.24		3.39	

3.5 Discussion

The experiment results allow us to give a partial answer to the question of "how accurate is a drone-based survey." Because of the complexity of the question, it is difficult to provide a single answer. However, the study found that the accuracy of drone-based surveys ranged from 0.68cm (0.022 feet) to 0.91cm (0.030 feet) horizontally, 0.09cm (0.003 feet) to 0.81cm (0.027 feet) in the vertical direction and 1.46cm (0.048 feet) to 2.22cm (0.073 feet) in the XYZ plane given the optimal altitude (38m) and equipment (P4P) tested in this experiment. There are several important caveats to this statement. First, it is based on commonly used equipment and not the most advanced equipment available. Second, it is based on the best flight altitude conducted in this study and not necessarily the optimal altitude for all cases. The researchers anticipated the 13m (40 feet) altitude to be ideal and did not expect to be unable to create accuracy models from that data. The optimal flight altitude would have been somewhere between 13m (40 feet) and 38m (125 feet). The researchers could have also included additional oblique (angled) photos to improve the model but that was not included in the experiment. The third important caveat is that the models were created given reasonable post-processing measures. The researchers could have invested hundreds of hours adding manual tie points but those efforts would unlikely be performed in practical applications so were not included in the experiment.

Photometric surveys have their place in the industry and will likely be used more and more as the technology, software, and practices improve as well as a general acceptance of the technology. Generally speaking, traditional survey techniques yield more accurate locations than photometric surveys on point-by-point comparison. Measurements with a total station are commonly sub-centimeter of the true location. However, the key advantage that drone-based surveys offer is the number of points that are created and the speed in which they are collected. In the experiment, it took two highly trained professional land surveyors 3 hours to locate the 31 points in the two fields. It took approximately a third of the time to fly a mission and create a model and over 25,000 points were computed. When the precision of a specific point(s) is needed, traditional techniques should be used. However, when a high quantity of points is desired or if the terrain is difficult to survey with traditional methods, drone-based photometric surveys are a very practical solution.

There were several key lessons that were learned from the study. The first is that some of the commonly accepted photogrammetric strategies don't always work. Specifically, when the experiment's methodology was created, it was assumed that the missions at 13m (40 feet) would be used to create models with the highest accuracy. It was found that there were insufficient distinguishing features in the grass field for the SfM software to accurately create the models. It was only when the images were captured at a higher altitude where enough distinguishing features were found to create the needed keypoints and tie points for an accurate model. Another deviation from common thought that this study makes plain is that the quality of the survey is not determined by the cost of the aircraft. The P4P had a higher megapixel camera and created a better photogrammetric survey than the Zenmuse X5 camera mounted on the M210RTK. The P4P, which has an integrated camera, has a retail cost of approximately $1,500 dollars US. Setting aside the cost of the M210RTK aircraft, the Zenmuse X5 camera alone has a retail cost of approximately twice that.

CHAPTER 4

Stockpile Volume Calculations Accuracy

4.1 Methodology

The accuracy of drone-based stockpile calculations was tested in two phases. The first phase was to conduct an experiment using a 3D object with a known volume. The second phase was to use an active state DOT borrow pit and compare the drone-based quantities with the quantities determined by a professional land surveyor. The following sections explain the two-phase in more detail.

4.1.1 Phase 1: Pyramid Experiment

For the first phase of testing, a two-acre test field was secured. The test field was an open field with grass cut short and no trees or other obstructions. In the test field, 17 aerial targets were evenly distributed. The aerial targets were 12”x12” with a black and white checkerboard pattern making it easy to locate the center from drone imagery. The targets were then located by the surveyor using a GeoMax Zoom 80 2" reflectorless robotic total station. In the center of the field, a cardboard pyramid was erected. The pyramid was constructed with 3 feet x 3 feet x 3 feet cardboard boxes (1 cubic yard each). The base was made of nine boxes, the middle tier had four boxes, and the top tier had one box. Figure 1 is a picture using a standing adult for size reference. The total volume of the pyramid was 378 cubic feet (14 cubic yards).

Figure 4.1: Cardboard pyramid stockpile simulation.

The drone used in the experiment was a DJI Phantom 4 Pro equipped with a 20-megapixel RGB camera. This is a commercially available drone and commonly used for construction and surveying activities. Six pre-programmed missions were created using the Pix4D capture app. Each of the pre-programmed missions created a flight path for the drone to take images at regular intervals. Three of the missions collected data at 125 feet. The altitude of 125 feet was chosen as it is high enough to avoid most trees and other obstruction but still close enough to collect high-resolution images of the ground. The images were all nadir (straight down) and had an overlap of 80%. Three iterations (A, B and C) of this mission were completed to see if the results of the models were repeatable. Two of the pre-programmed missions captured “oblique” (angled) images by circling the pyramid at 35 feet and 55 feet altitudes. The drone was programmed to take an image at 10-degree intervals so a total of 36 oblique images were collected with each mission. The last pre-programmed mission was set at 350 feet and also collected images at an 80% overlap. This elevation was selected as it was near the 400 feet maximum altitude allowed by the FAA and still maintained a reasonable safety margin. Descriptions of the six missions are provided in table 4.1.

Table 4.1: Pre-programmed missions with descriptions.

Mission Title	Description
125’-A	Nadir (straight down) images captured at 125 feet elevation (iteration 1). 80% overlap between images.
125’-B	Nadir (straight down) images captured at 125 feet elevation (iteration 2). 80% overlap between images.
125’-C	Nadir (straight down) images captured at 125 feet elevation (iteration 3). 80% overlap between images.
35’-Oblique	Circular mission around the pyramid at an altitude of 35’. Oblique (angled) images were captured at 10-degree intervals around the pyramid.
55’-Oblique	Circular mission around the pyramid at an altitude of 55’. Oblique (angled) images were captured at 10-degree intervals around the pyramid.
350’-A	Nadir (straight down) images captured at 350 feet elevation. 80% overlap between images.

When the drone captures an image, it embeds metadata within the image file. Most relevantly for this experiment, it includes the GPS coordinates of the drone when it took the image (accuracy = +/- 3 feet) and the angle of the camera. With the image and the metadata, 3D surveys can be created with structure-from-motion (SfM) software. For this experiment, “ContextCapture,” provided by Bentley Systems Incorporated was used as the SfM software and created the surveys and stockpile volumes.

The accuracy of the surveys was measured in two ways. First, the pyramid erected in the test field had a known volume of 378 cubic feet. The volume of the pyramid in the survey was computed and compared to this known value. The second means of measuring accuracy was the Check Point error (CPe). In the test field, 17 aerial targets were geo-located by the surveyors. Four of these targets were used as ground control points (GCP) to locate the survey on the earth’s surface. The other 13 targets were checkpoints and not used to create the model but rather test for accuracy. The CPe is the distance from the known, geo-located center of the target from where it was computed in the 3D survey. The CPe will be provided as a horizontal CPe (ground surface) and vertical CPe (elevation).

By examining the injury distribution based on the month, it was discerned that most crashes occurred in August (124k) and least in February (48k). The evaluated data is presented in Table 4 and corresponding Figures 13 and 14.

4.1.2 Application in Active DOT Borrow Pit

An active South Carolina Department of Transportation (SCDOT) borrow pit was used in the second phase of the study. The portion of the borrow pit used had an area of .6 acres and an elevation change of 55 feet. A professional land surveyor with the SCDOT located eight aerial targets. Similar to the pyramid experiment, some of these points were used as GCP in the survey and the others as checkpoints to measure accuracy. The four GCP were also used as corners of the borrow pit measured. Calculations for how much earth would need to be cut and filled to level the plane of the four points were computed using the SCDOT conventional methods and with drone images and SfM software. The volume calculations and contour maps were compared using both techniques.

4.2 Results

4.2.1 Accuracy without the Use of Ground Control Points

The first phase used a cardboard pyramid as a control structure. It is known from the literature that adding GCPs increases the accuracy of the drone surveys; however, these are often not available to constructors. The first experiment was to test the accuracy of the survey without using GCPs. Most commercial-grade drones, including the one used in this experiment, are equipped with an onboard GPS unit. The GPS is used to navigate as well as imprint in the image file the coordinates of the drone and camera angle when the image was taken. The GPS unit is far from survey grade and has an accuracy range of a yard or more from actual. The accuracy of this first survey, titled “Flight 125A – 0 GCP” is shown in table 4.2. The “average ground resolution” (AGR) is the average area of the survey field that is represented by one pixel of the image. The higher the drone’s altitude when collecting data, the more of the field is represented by a single pixel. Images collected closer to the survey will have a smaller AGR and have more resolution in the surveys created. The average size of one pixel in the Flight 125A – 0 GCP survey was .03 feet. A measure for how well a photometric model was constructed is the RMS reprojection error (RMSe) typically measured by the pixel. A model with an RMSe than one is generally considered a “high quality” reconstruction (Bentley, 2019). This does not necessarily mean that the accuracy is high as it could be reconstructed with a large AGR. A low reprojection error simply means that the images were stitched together well. Table 4.2 also provides horizontal and vertical CPe. This survey did not include any GCPs and relied on the aircraft’s GPS to locate the model on the earth’s surface. For the Flight 125A – 0 GCP survey, the average computed distance from the seventeen checkpoints from the true location is 8.2 feet horizontally and 490.6 feet in the vertical direction. This makes the point that GCPs are needed if you are using drone-based surveys and require absolute accuracy.

Table 4.2: Results of surveys created from phase 1 images.

#	Survey Name	AGR (ft)	RMSe (pixels)	Horizontal CPe (ft)	Vertical. CPe (ft)	Actual volume (cu. ft)	Computed volume (cu. ft)	Percent Diff.
1	Flight 125A - 0 GCP	0.03	0.72	8.20	490.6	378	477	26.3%
2	Flight 125A - 4 GCP	0.03	0.75	0.03	-0.02	378	384	1.5%
3	Flight 125B - 4 GCP	0.03	0.75	0.04	-0.02	378	389	2.9%
4	Flight 125C - 4 GCP	0.03	0.76	0.04	0.03	378	390	3.3%
5	Flight 125A with Obliques - 4 GCP	0.03	0.64	0.04	0.01	378	386	2.1%
6	Flight 350A - 4 GCP	0.09	0.79	0.05	0.06	378	434	14.8%

Volumetric calculations do not require absolute accuracy however. The cut and fill volume of a stockpile is based on a relative plane such as the surrounding ground surface. For the calculations in this experiment, the flat surface around the pyramid was the relative plane in which the cut calculation was benchmarked. Figure 2 shows a screenshot of the software where four green spray-painted dots are used as corners of the plane in all of the survey models created. The Flight 125A – 0GCP survey estimated that the pyramid had a volume of 477 cubic feet which is 26.3% greater than the known value of 378 cubic feet. This level of error makes the model all but unusable for most construction purposes. However, the accuracy of this model was significantly improved when GCPs were added to the survey.

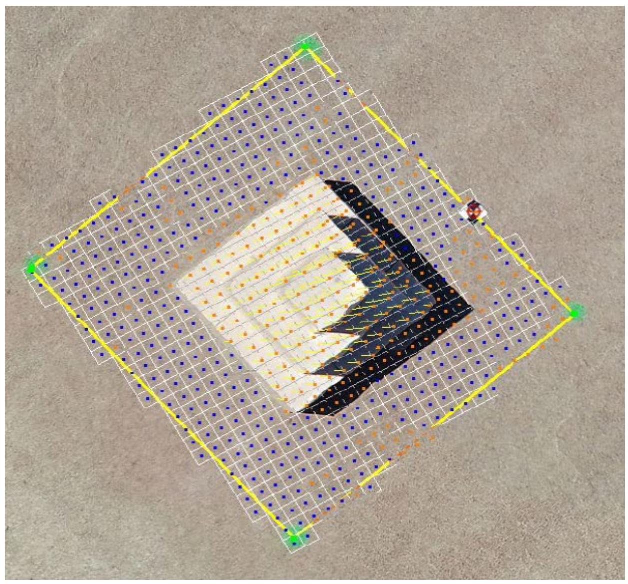


Figure 4.2: Volumetric calculation in Bentley's ContextCapture.

4.2.2 Optimal Number of Ground Control Points

Adding GCPs add both absolute and relative accuracy to the drone-based surveys. However, surveying GCPs can be time-consuming and there is a diminishing return with additional GCPs. Bentley recommends that GCPs be spaced 20,000 pixels from one another which in this case (AGR = .03 feet) would be every 600 feet (Bentley, 2019). The test field was approximately 250 feet x 350 feet so three GCPs should have been sufficient. To test this recommendation, the researchers created six surveys with images from Flights 125A sequentially adding one GCP with each survey. The median 3D error of the remaining checkpoints was used to evaluate the accuracy of the model and determine the optimal number of GCP that should be used for the rest of the surveys. The results of the surveys can be found in table 4.3. The models with zero, one, and two GCPs all were over 490 feet from the true location. However, once the third GCP was added, the median 3D error was reduced to .12 feet and then to .08 feet when the fourth GCP was added. For the remainder of the experiments, the researchers used four ground control points as an "optimal" number. The remaining 13 aerial targets were used at checkpoints.

Table 4.3: Optimal number of ground control points.

Survey Name	GCP 3D Median Error (ft)
Flight 125A - 0 GCP	490.45
Flight 125A - 1 GCP	491.47
Flight 125A - 2 GCP	490.71
Flight 125A - 3 GCP	0.12
Flight 125A - 4 GCP	**0.08**
Flight 125A - 5 GCP	0.09

4.2.3 Accuracy when Ground Control Points Used

As expected, when 4 GCPs were added to the Flight 125A survey, the accuracy significantly improved. Table 4.2 shows that survey Flight 125A – 4 GCP computed the pyramid to have a volume of 382 cubic feet which is 1.5% more than the actual volume. The experiment was repeated two more times with images captured with the same pre-programmed flight path but at different times of the day. The results of the survey "Flight 125B – 4 GCP" and "Flight 125C – 4 GCP" are found in table 4.2. All three surveys had very similar horizontal and vertical CPe. The survey created from flights 125B and 125C overestimated the volume by 2.9% and 3.3% respectively.

4.2.4 Impact of Oblique Images on Accuracy

The surveys described above were created from nadir images only. When recreating a 3D model, it is often helpful to add oblique images so that the sides of the objects can be reconstructed more accurately. The researchers tested to see if the accuracy of the volumetric calculations would improve if oblique images were added. The drone was programmed to circle the pyramid at 35 feet and 55 feet above the ground capturing images at 10-degree intervals. Those images were added to the data set from Flight 125A – 4 GCP. The accuracy of the new survey can be seen in table 4.2. There was a marginal improvement in the reprojection error and vertical CPe compared to the Flights 125A, B and C. The volume of the pyramid was estimated to be 434 cubic yards which was 2.1% greater than actual. This is also very similar to what was seen with the surveys without the oblique images. With the conditions of this specific experiment, oblique images did not improve the volume estimate.

4.2.5 Impact of Altitude on Accuracy

There is an inverse relationship between the altitude in which the data was captured and the accuracy of the models. However, the higher the drone is flown, the more land area is captured with a single image reducing the flight time needed to complete the survey. For the test field used in this experiment, it took approximately five minutes from takeoff to landing to collect the images at 125 feet. It took the drone approximately half that time to collect images of the same area at 350 feet. While relatively insignificant for this small testbed, doubling the flight time may be a significant limitation when surveying a larger site. The results of the survey created from images captured at 350 feet can be seen in the last row of table 4.2. Because of the higher altitude, the AGR was .09 feet which is three times the pixel size of a similar survey created from data collected at 125 feet. Despite being constructed with lower resolution images, the model was stitched together well as represented with a reprojection error of .79 pixels and CPe's comparable to the other surveys. There was a significant decrease in volumetric calculation accuracy however. The

"Flight 350A – 4 GCP" survey computed the pyramid to have a volume of 434 cubic feet which is 14.8% larger than its known volume. This is significantly larger than the inaccuracies seen with data collected at 125 feet which ranged from 1.5% - 3.3%.

4.2.6 Application of Drone Survey at SCDOT Borrow PitImpact of Altitude on Accuracy

The second phase of the study was to compute volumes at an active SCDOT borrow pit and compare it with conventional practices. Images from 90 feet, 125 feet and 200 feet were used to create the survey. As shown in Table 4.4, the AGR was .04 feet and the RMSe was .70 pixels which are comparable to what was found with phase one, 125 feet surveys. At the borrow pit, five GCPs and three checkpoints were used. The horizontal CPe ranged from .005 feet - .016 feet and the vertical CPe ranged from .019 feet - .065 feet which is also fairly equivalent to what was seen with the phase one surveys.

Table 4.4: Borrow pit survey accuracy.

SCDOT Borrow Pit Survey	AGR (ft)	RMSe (pixels)	Check Point Error Horizontal (ft)	Check Point Error Vertical (ft)
Check Point 1			0.005	0.019
Check Point 2	0.04	0.70	0.016	0.065
Check Point 3			0.012	0.022

A base plane elevation was created by averaging the elevations of four GCPs. Cut and fill calculations were computed to determine the fill needed to level the surface to the base plane. Table 4.5 shows that the photometric survey calculated a total of 3,217 cubic yards of earth would need to be cut from the site to level the plane. This was about 10% more than what was computed by the professional land surveyor (2,900 cubic yards) using a robotic total station. As the exact quantities of the borrow pit are not known, it is difficult to make definitive conclusions on the accuracy. However, assumptions can be made based on the resolution of the output. Figure 3 provides a comparison between a conventional 3D contour plan created using 250 points from the total station and the photometric survey using 239,700 points captured by the drone. The drone-based survey has significantly higher resolution and captures the shape of the surface much more precisely. Figure 4 is a blow-up of the embankment below the excavator. Notice that in this view, even the tracks of the excavator are visible.

Table 4.5: Comparison between photometric and conventional survey quantity calculation

.Quantity	Photometric Survey	Conventional Survey
Cut (cu yd)	3,511	3,039
Fill (cu yd)	295	139
Total Cut (cu yd)	3,217	2,900
Difference (cu yd)	317	
Difference (%)	9.8%	

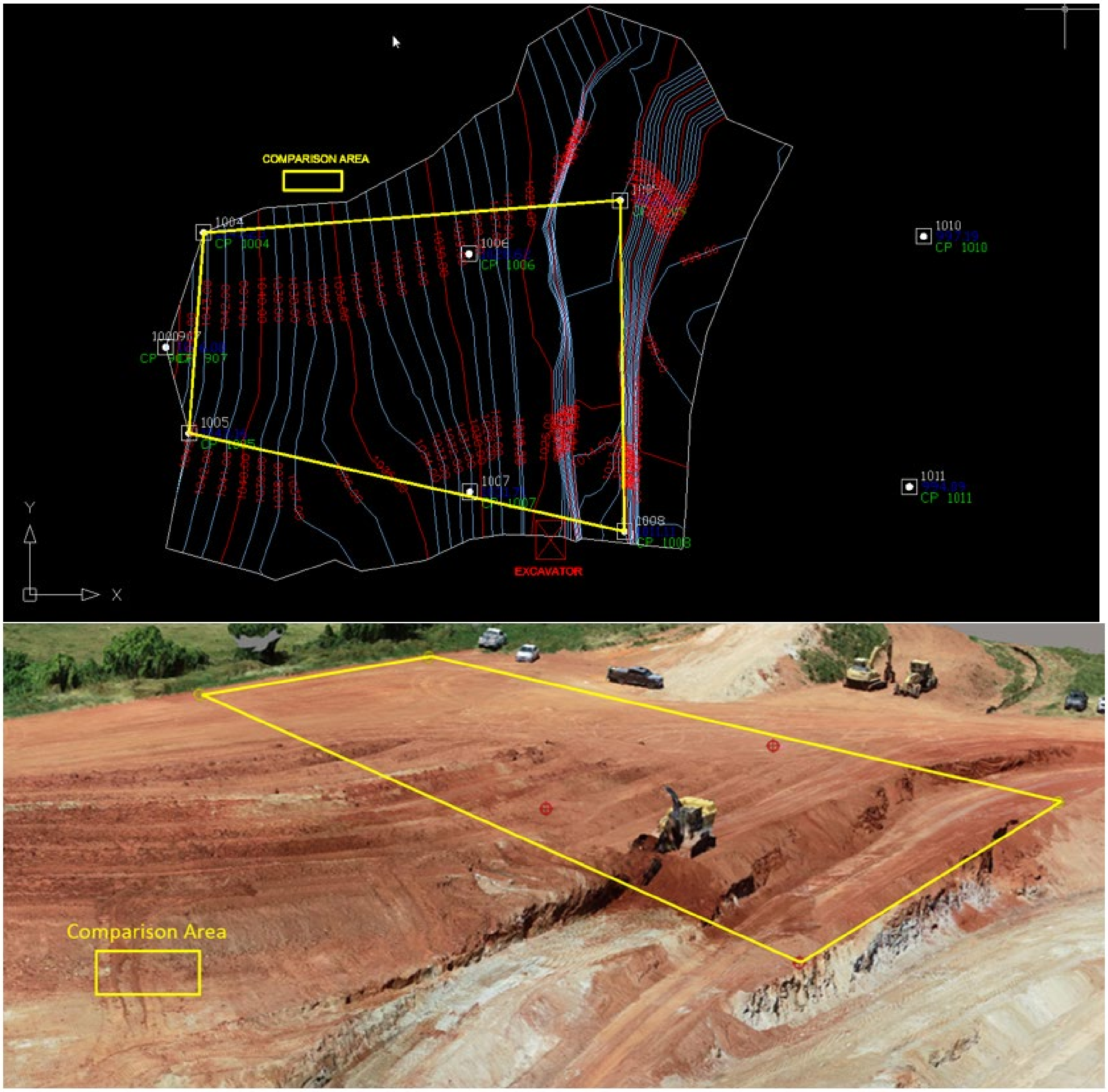


Figure 4.3: Comparison between conventional topographic (top) and photometric (bottom) survey.

Figure 4.4: Embankment area of photometric survey.

4.3 Discussion

This study demonstrates that commercially available drones and software can be used to create models with a high degree of accuracy. In the first phase of the study, a 378 cubic foot pyramid was used to simulate a stockpile. The horizontal and vertical error of the drone survey created from images collected at 125 feet above the surface was consistently within .03 feet which is within tolerance for many construction activities. The drone surveys also estimated the simulated stockpile very well with three different surveys computing the volume with 3.3% or better of actuals. In the second phase, volumetric calculations using conventional and drone-based surveys were compared. There was nearly a 10% difference in the volume computed. Given the accuracy seen in phase one and the difference in volume estimates in phase two, it appears as if there could be some significant gains by the SCDOT if this technology is deployed to supplement current practices.

CHAPTER 5

UAS Drone Bridge Inspection

5.1 Methodology

To evaluate the effectiveness of using a UAS to support a bridge inspection team in South Carolina, two primary experiments were conducted using the same test bridge. The purpose of the first experiment was to evaluate how many of the defects the drone could identify given optimal conditions. For this experiment, the inspection team that recently inspected the test bridge using a UBIT was tasked to re-inspect the bridge but this time using only the drone. The inspection team had access to the previous inspection report so the deficiencies were known. The results gave the researchers an understanding of the maximum amount of deficiencies that could be seen given optimal conditions. Essentially, could the bridge inspection engineers (BIEs) find the deficiency if they knew it was there? The second experiment was designed to evaluate the number of deficiencies that could be identified using a drone when the BIE did not know what deficiencies were present. For this experiment, an inspection crew from another district, who were unfamiliar with the test bridge, was given the same task of inspecting the bridge with only the UAS. In these sections to follow, the methodology for how the research team selected the test bridge, what equipment was chosen and the specifics of the two experiments will be elaborated on.

5.1.1 Shadowing Bridge Inspection

The first step in the investigation was for the researchers to shadow an inspection team as they assessed bridges in their district. South Carolina is divided into seven districts each with at least one bride inspection team. The bridge inspection team from district seven supported this study. The team consisted of three certified BIEs and in some cases a summer intern (figure 1). The local SCDOT counties provided traffic control when needed. The researchers shadowed the BIEs primarily to have a better understanding of the type of deficiencies that were common and the methods for how those deficiencies were found. Another important objective was to observe bridges that could serve as the test bridge in the study's experiments. The BIEs from district 7 were informed about the goals of the project and were consulted about which bridges they thought could be good candidates. The researchers coordinated their shadowing schedule so they could observe these bridges.

Figure 5.1: Traditional inspection with UBIT.

5.1.2 Selection of Test Bridge

Desirable characteristics of the test bridge were that it be of significant enough scale to benefit from a drone inspection and that there were not significant obstructions making drone flight dangerous. A total of 12 bridges were identified by the BIEs as potential candidates and observed by the researchers as they were assessed using traditional methods. The structure varied from concrete, steel, and timber pile caps. Their length and number of lanes of traffic also varied. Some of the bridges were over rivers while others had streets, rail or a dry stream bed under them. Ultimately, the Bates Bridge was selected (see figure 5.2 and 5.3). The Bates Bridge is a two-lane bridge over the Congaree River located southwest of Columbia. It is approximately 0.3 miles long and has a concrete structure. Three factors made this bridge the most desirable of the bridges evaluated for the experiments. First, a UBIT truck is required for the traditional inspection and as this bridge has two lanes of travel (one lane of travel each way), there was significant traffic disruption during the inspection. Second, the Bates Bridge had very little vegetation surrounding it making flying the drone much more manageable. The third reason this bridge was selected was that a large parking lot was located under the northeast side of the bridge. This parking lot served a boat dock located under the bridge. The parking lot made an excellent staging area to conduct the experiments.

Figure 5.2: Bates bridge #1.

Figure 5.3: Bates bridge #2.

5.1.3 Pre-Inspection Trial Run

After the test bridge was selected, a "mock" inspection was performed without the BIEs (figure 5.4. The purpose of the mock inspection was not just to evaluate the drone's capability but to make sure all logistical issues were accounted for prior to having the BIEs on site. The researchers captured many images from above and below the bridge deck so 3D reconstruction models could be created later. The BIEs also flew the drone under the bridge to observe aspects of the bridge they believed the BIEs would want to observe. This was done to get an understanding of how the drone would respond as the GPS signal was repeatedly lost and then reacquired. The bridge location also had high-voltage power transmission lines nearby and it was important to test how those impacted flight controls

Figure 5.4: Bates bridge mock inspection.

5.1.4 Equipment Used

The research team had originally planned to use a Sense Fly Albris quadcopter drone as it had been successfully tested with other bridged inspections (Lovelace, 2015; Wells and Lovelace, 2017). However, this aircraft was discontinued by the manufacturer before the project was awarded. The aircraft that was selected to replace it was DJI's M210 RTK (version 1) (figure 5.5). The M210 RTK is a general-purpose quadcopter in DJI's enterprise line. It can support several different sensors including the Zenmuse Z30 camera (Z30). The Z30 sensor was used for this experiment because it has a 30 times optimal zoom. This allowed for detailed observations without having to fly the drone in close proximity to the bridge structure. This model also features a real-time kinematic (RTK) positioning ground control station (figure 5.6). The RTK unit was located on a tripod away from the bridge. The RTK unit located itself via satellite and then help position the M210 RTK drone when it flew in a GPS denied environment. TB50 and TB55 are two different battery types supported by the M210. (The second generation of the M210 is only supported by TB55 batteries.) TB50 is the smaller of the two and will sustain flight times of approximately 17 minutes when the Z30 is mounted. The TB50 was selected because, unlike the TB55, the manufacture sells a battery charging hub that can charge eight batteries at a time (figure 5.7). The research team found that a supply of 16 TB50 batteries was sufficient to continually charge batteries at the same rate they were depleted. Like most bridge sites, power was not available so a generator was procured. The charging station at full capacity drew 1,000W so a 2,000W generator was used to also support various other electronics like laptops, controller battery chargers, tablets and cell phones. This aircraft allows for the camera to be controlled by a second person with another controller. For this experiment, two Cendence controllers with 7.85-inch CrystalSky monitors were used (figure 5.8). The pilot controlled the aircraft while the BIE controlled the camera. The controller and monitor are both powered with a WB37 battery. The researchers found that four batteries in use, while another four were charging (eight total), were sufficient to keep the two controllers continually operational. Additional equipment and materials used included a 12'x12' tent, table, walkie-talkies, hard hats, safety vests, air horns, sunscreen, insect repellant, water/snacks, first aid kit, and safety cones (figure 5.9 and 5.10).

Figure 5.5: DJI M210 RTK UAS used in inspection.

Figure 5.6: RTK ground station.

Figure 5.7: TB50 battery charging hub.

Figure 5.8: Cendence controllers with CrystalSky monitors.

Figure 5.9: Basecamp.

Figure 5.10: Set up.

5.1.5 Set-Up of the Experiments

As stated earlier, the purpose of the first experiment was to understand how much of a traditional bridge inspection could be performed with a UAS given optimal conditions. The primary purpose of the second experiment was to verify how much could be inspected given real-world conditions the deficiencies were not known ahead of time. The team for both experiments consisted of the principal investigator (PI) and co-investigator who are faculty at state universities. It also consisted of several SCDOT employees; two of which are in the Department of Engineering Technology & Research and the others were BIEs. For the first experiment, the BIEs had been the lead inspectors who assessed the test bridge approximately 1 year prior. In the second experiment, the BIEs were from a different district and were unfamiliar with the bridge. Several graduate students also assisted with the experiment. Prior to experiments, the air space of the bridge was determined to be class G and that no authorizations were needed. It was checked again the day of and if any temporary flight restrictions (TFR) or notice to airmen (NOAM) were published by the FAA. The "base camp" consisted of a 6' table under a tent with sidewalls (figure 5.11). The sidewalls proved very helpful when reducing glare on laptop screens and keeping the equipment out of direct sunlight. The generator was located approximately 50 feet away so that the noise and exhaust were not an issue (figure 5.12). The heat was a safety concern so a truck was located and left running with the air conditioning on. This truck was designated as a cool-down space and used exclusively for this purpose (figure 5.13). The PI began the experiment with a safety talk where he identified the major hazards such as manned aircraft, traffic, boats and contact with the UAS's propellers (figure 5.14). The team intentionally stayed out of the line of site of traffic as they did not want to be a distraction. The drone was either flown under the bridge or a minimum of 150’ above the bridge deck. Two participants were charged with watching for cars around the base camp as well as for looking for manned aircraft. They were issued walkie-talkies and also air horns for emergency notification if operations needed to stop immediately. Prior to the experiment, the aircraft was inspected using a pre-printed inspection checklist. The aircraft performed a series of test maneuvers to verify it was responsive to the controls. For both experiments, one of the BIEs was designated as the lead and was given control of the camera. The control of the aircraft remained with the pilot and PI at all times. A brief tutorial on how to operate the camera controls was given where the BIEs quickly became comfortable with the controls (figure 5.15). In the first experiment, the BIEs had access to the inspection report they create the previous year. The inspection report categorized deficiencies by major items such as “deck”, “bearings” and “expansion joints.” For the first experiment, the report was reorganized by “span” to better mirror how the drone would observe the bridge one span at a time.

Figure 5.11: Tent and table.

Figure 5.12: Generate.

Figure 5.13: Cooldown truck.

Figure 5.14: Safety talk and briefing.

Figure 5.15: Flight controls briefing.

5.1.6 Evaluation of Drone Performance

The inspection report, which was created approximately one year prior to the experiment, contained 120 inspection comments. Some of the inspection comments were very specific such as “Span 11 - had typical diagonal cracking in the web of beam five.” Other comments were more general such as “hairline longitudinal cracking throughout the deck.” During the first inspection, a three-person crew inspected the bridge. The PI piloted the aircraft, the BIE controlled the camera and a third “note-taker” called out the deficiencies from the inspection report (figure 5.16 and 5.17). The pilot and the BIE positioned the aircraft and camera to see if they were able to observe the deficiency. The note taker would then record either “yes” or “no” as to if the deficiency could be observed sufficiently for the BIE to determine its condition. One of the quantitative outcomes of this experiment was to determine what percentage of the inspection comments could be sufficiently observed with the UAS.

Figure 5.16: Flight crew #1.

Figure 5.17: Flight crew #2.

The second experiment was similar; however, a different BIE controlled the camera (figure 5.18). The inspection report was also not provided to the BIE. The BIE was told that he was tasked with inspecting this bridge using only the drone. As with the first experiment, the PI piloted the aircraft while a third person took notes.

Figure 5.18: Flight crew #3.

5.2 Results

5.2.1 First Bridge Inspection Observations

The first experiment was completed between 8:00 am and 3:00 pm on June 25th, 2019. Timestamps on the observations are attached in order to be able to gauge the length of the experiment, approach, and longitudinal information which are plotted in figure 5.19. Throughout the experiment, the crew pointed out either negative or positive aspects of the technology as a potential replacement to traditional methods.

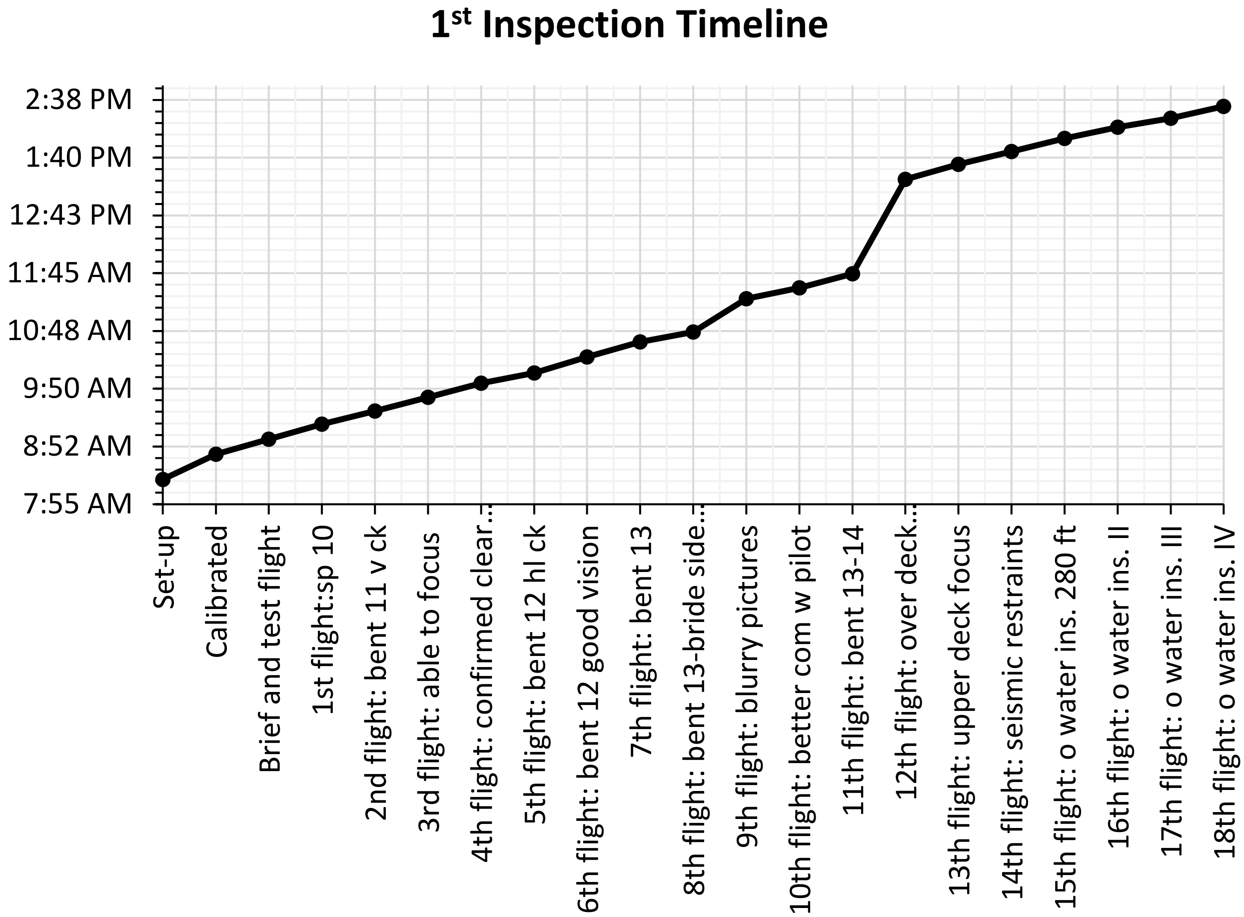


Figure 5.19: Experiment #1 observation time stamp.

Between 8:20 am and 8:45 am, the team started to set up the camp and equipment. Between 8:45 am and 9:00 am, the drone was calibrated, the BIE was briefed about the camera and 2nd pilot controller on the ground. Per testing, the BIE was asked to confirm “yes” or “no” if the noted were clearly confirmed from the checklist of the last year’s inspection. Battery switches took about a minute each given a crew member was responsible for this task. In this study, end times of the flights include the battery changing times at 35% battery life remaining.

During the first flight, 9:00 am-9:15 am, inspection on the 10th span was carried out. Camera zoom was investigated. The most critically, bearings were checked. They were confirmed as too thin to see in detail and replied as “no” (figure 5.20 and 5.21). During this flight, zoom in, out, orientation with respect to beams, and the glare was figured out. At this stage, a significant amount of time was spent seeing the specific location of the previous crack noted. Both with checklist and drone piloting were coordinated successfully. Initially, it was asked if the pilot would be able to move up and down without being uncomfortable with the proximity of the structure. As the pilot’s and aircraft’s performance were improved, the BIE was later able to guide the pilot to specific spots with accurate distances. Moreover, a method was developed to scan through different sides of the bridge efficiently. This included mainly quickly finding good angles, zoom in and out, and to avoid sun glare. Note that the orientation initially was asked to pilot and a communication procedure with the pilot was demanded which later evolved to comfortable with orientation even if the aircraft was not seen. Except for one or two instances, the camera was very responsive, pictures were clear at all zoom levels. The aircraft was also very responsive to directions to the BIE. It was also noted “yes” for being able to see almost all horizontal, vertical hairline and map cracks even in inch scale.

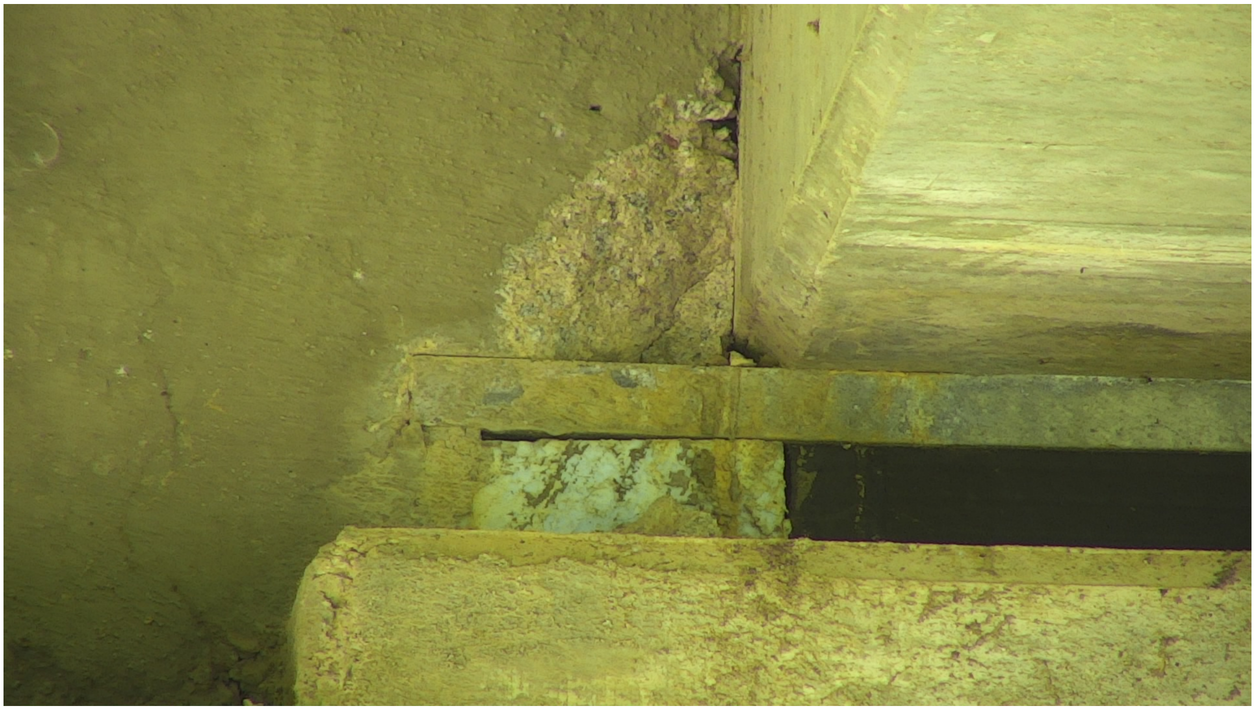


Figure 5.20: Bearing unable to see sufficiently #1.

Figure 5.21: Bearing unable to see sufficiently #2.

During 2nd flight between 9:18 am-9:28 am, communication was a lot smoother, more responsive, and scanning for deficiencies was faster. Minor bouncing with the aircraft was noted that required patience to focus. At 9:23 am, bent 11 was inspected and previous notes were confirmed where mainly vertical hairline cracks were detected (figure 5.22). In this flight, the BIE started to develop a systematic method for taking pictures and videos. The pilot was asked to call the beam number for better referencing and improving the coordination.

Figure 5.22: Hairline cracking observed with the drone.

In the 3rd flight between 9:33 am-9:42 am, the pilot started to call where the aircraft is at and the beam number. The BIE confirmed picture quality and was able to see vertical cracks clearly. Zooming was never an issue from any aircraft distance (usually about 8 feet) from a beam and edge etc. The BIE was able to get easily get closer to an interesting, pre-planned, or critical section and region.

During 4th Flight, 9:43 am-9:56 am, BIE continued to check the points from the inspection list with clear vision. It was noted that a detailed schedule and a pre-inspection detailed plan can improve the battery life and duration of the inspection.

On the 5th flight from 9:57 am-10:06 am, bent 12 was inspected. The BIE showed the first fatigue. This is understandable as the controller weighs 3 lbs. Inspection activities require high attention, long monitoring, and coordination. Both the pilot and BIE needed a break after about 1.5 hours. Sun glare was noted as an issue. By this time, the BIE was able to guide the aircraft and camera angle to be able to avoid sun glare effect. This certainly adds time and additional attention to the process. Hairline cracks were successfully noted.

During 6th flight, 10:07 am-10:22 am, on the other side of bent 12, the team started inspection over less accessible over the vegetation less accessible beams. The references left from the previous inspection were seen. In this section, bearings observed to be a problem. Visuals for other targets stated to be good. The first time, a drift was noted differently than the bouncing observed during the 2nd flight. Technically, the distance of 30 feet at 30x zoom with drift resulted as harder to compensate with camera control.

In the 7th flight, 10:27 am- 10:37 am, glare was noted at the 13th bent. The inspection was conducted from longer distances over vegetation. The checklist was included more this time. As the aircraft was over the vegetation with low battery warning, it was brought back more cautiously. The aircraft showed a brief loss of control.

During the 8th Flight, 10:38 am- 10:47 am, after inspecting bent 13 successfully, the side of the bridge was scanned. This task helped the team to visualize the UAS-based inspection's advantage of safety, not closing lanes and the quality of image angles. The speed at this point was noted to be 3rd slower than traditional methods.

Between 10:50 am-11:08, there was a controller malfunction and required rebooting.

On the 9th flight, 11:08 am- 11:20 am, pictures got blurry so batteries were changed and the system rebooted.

During the 10th flight, 11:21 am-11:31 am, pictures' resolution was corrected. By this time, communication got much better with the pilot and zooming into targeted points.

In 11th flight, 11:35 am-11:45 am, spans 10 to 14 were scanned. Detailed pictures were taken on the bridge side. It was noted that taking pictures on the side of the bridge is a difficult task in the original inspection. The side of the bridge was quickly scanned.

After another break, 12th flight from 1:10 pm-1:19 pm, the camera was mounted at the bottom of the aircraft. Over the deck inspection at heights 180 to 300 feet was conducted. Transverse cracking was seen with no problem. Guardrail conditions were clearly observed. During this inspection, the BIE was comfortable zooming in different locations without any difficulty. Camera control was even smoother. This might also be due to no obstacles at this altitude and open view. The aircraft was controlled 700 feet away with no problem. Hence, coordination was improved. Expansion lines, as well as sides of the bridge, were checked easily.

During 13th flight 1:20 pm-1:34 pm, the upper deck of the bridge over the river was inspected. A series of high definition videos was recorded and pictures were taken focusing on possible deficiencies.

In 14th flight 1:35 pm-1:47 pm, seismic restraints under the bridge were inspected successfully. Both pilot and BIE team was more comfortable maneuvering around columns. Although the camera was at the bottom, the BIE was able to coordinate comfortably with angles. Cracks were identified with no problem. Although the camera position was not switched, the quality was identical to the camera at the top of the aircraft.

During 15th flight 1:48 pm-2:00 pm, inspections over the water was started. Columns in the water were inspected easily. The team was able to control the aircraft and complete the inspections of bents up to 280 feet away.

During flights 16, 17, and 18, over 2:01 pm-2:11 pm, 2:11-2:20 pm, 2:24-2:32 pm, over the water inspections continued. The team was on the riverbank, the BIE was able to coordinate with the pilot to guide aircraft feet-by-feet in all directions to various beam sections and bearings. This clearly revealed the progress over a few hours.

Bearings were noted to be too thin to be seen, although a longer time was spent on them. Checking and coordinating took a longer time. Aircraft were also awaiting commands during these communications which meant precious battery usage. It was argued that with this approach quality of reach-haul inspection would be improved, the number of crew members for ad-hoc inspections can be reduced to as low as four team members. Safety and no lane closure was mentioned. Over the bridge inspection in time as well as modeling was discussed. The overall higher number of inspections can be feasible. The approach can be used to document before and after a flooding event as well as the state at the first construction. Thus, a time series of bridge and surroundings images could be stored very easily. It was pointed out that not replacing the detailed inspection, however, the benefit would be for off years and quick checks and inspections.

5.2.2 Second Bridge Inspection Observations

This section documents the experience from the second BIE's experiment with drone technology on July 17, 2019, between 8:00 am to 12:00 noon. As before, the timestamps on the observations were attached in order to be able to gauge the length of the experiment, approach, and longitudinal information (see figure 5.23). The team followed a procedure that would be followed in a traditional inspection. Bearings on both sides of the bridge were inspected going through the beams, i.e., zig-zag way, thus spanning the entire section without a miss. Lessons learned from the 1st inspection, a pilot, battery switching tech help, a BIE, and a checklist guide were able to successfully conduct the inspection with no issues (i.e., the team of four was sufficient for the test).

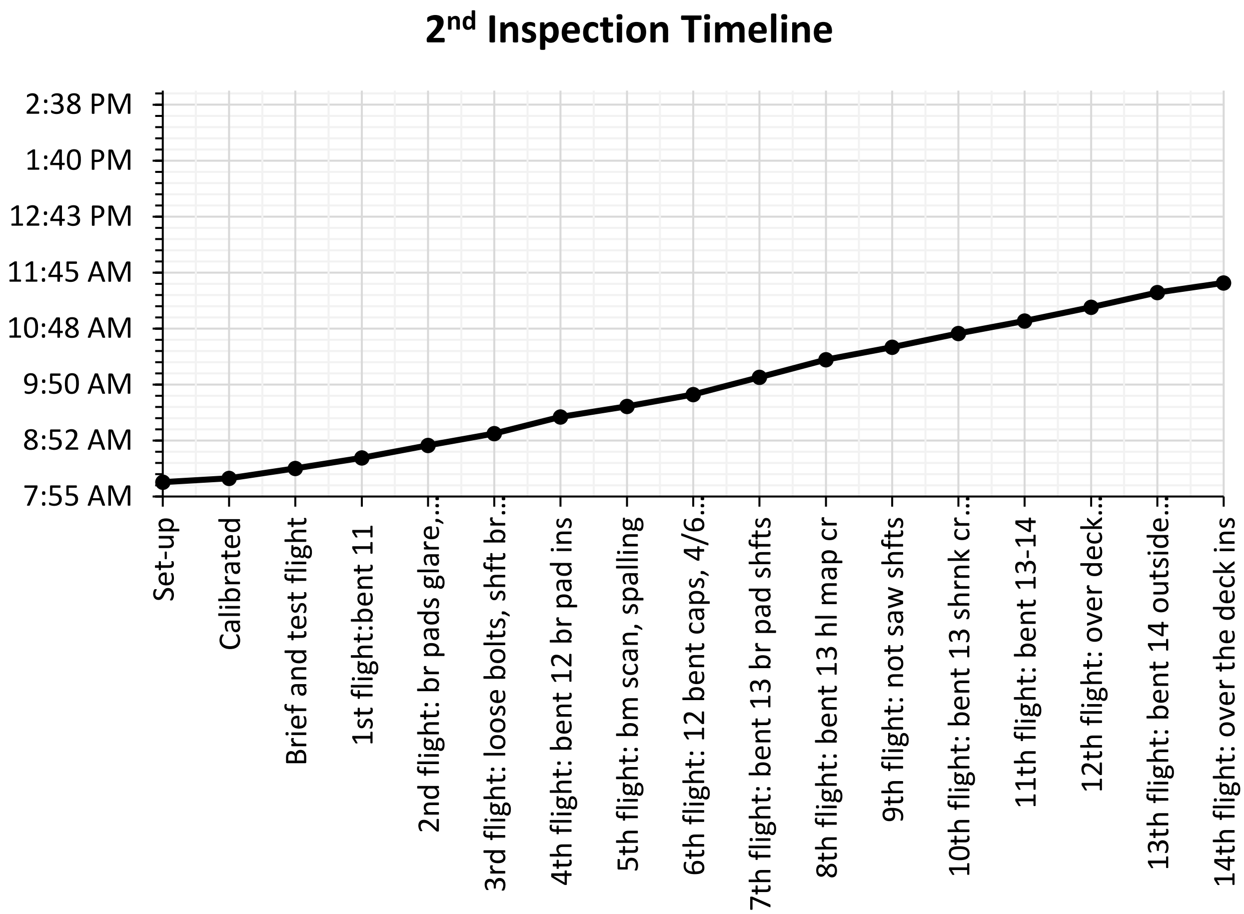


Figure 5.23: Experiment #2 observation time stamp.

Between 8:00 am-8:18 am, the team started to set up the gear and explained the equipment to the BIEs. No calibration was needed. The BIEs had a test flight with the camera (i.e., 2nd pilot controller). As with the previous inspection, it was asked to confirm if the BIE clearly saw the same observation or not with “yes” or “no”. A comment made by the BIE was if the UAS would come with a larger screen which is interesting from the user feedback perspective. Screen commands, zoom function, taking pictures, taking videos, adding notes, battery life warning, and communication were briefed.

In a test flight, 8:18 am-8:24 am, the camera zoom was checked. The team had the first issue of connection as GPS signal loss which resulted in frozen screens and image loss. Weak connections in the field may have caused it.

During the 1st flight, 8:24 am-8:35 am, the BIE started the inspection on 11th bent. It was noted that the flat bearings could not be inspected for expansions and shift when lined up due to mostly lighting. However, when tried with different angles and coordination with the pilot, they were seen. The BIE was able to deduce their states. Bearings on the outsides were seen fine. It should be noted that this took communication and angle search with the pilot. This method improved the performance of the overall inspection. As another note, after two set up experiments on a different bridge and a complete inspection on the same bridge, the pilot was also more comfortable to control the UAS and response to requests of the BIE. This observation would be indicative of a learning curve for a pilot operating under bridge inspection.

In 2nd flight 8:37 am-8:48 am, bearing pads were seen fine by the BIE. Angles that eliminate the glare were searched. The BIE was able to guide and find better angles and altitudes. Different than the previous inspection, the BIE did not get closer to surfaces. BIEs' scanning was also different when compared. Again this might be due to the pressure of observing the same details as last year's inspection. Communications got more efficient by this flight. Compared to touchpad zoom, a zoom joystick was observed to be more appropriate for this operation as immense zoom-ins and outs were required. This was interesting as user feedback for inspections. On beam two and 3, 6-inch diagonal hairline cracks were detected. Orientation confusion with respect to beams was not an issue during these inspections. This might be due to the pilot's experience and piloting in a systematic approach and clueing the aircraft position. Later this was commanded by the BIE as "next set of beams".

During 3rd flight 8:52 am-9:00 am, the BIE focused on loose bolts, gaps, bulging, and shifting of bearing pads. The BIE commanded to the points and the angles. Between 10th and 11th bents, loose bolts were detected. Due to RTK set up issues, the aircraft was brought back. After this flight, control of the UAS got smoother. It was noted by the BIEs team that 6-inch hairline crack detection was impressive, thus, yielding comfort and trust for the inspection with UAS. Cameras found to be providing sufficient performance.

During 4th flight 9:05 am-9:17 am, the BIE was scanning the beams very efficiently. The BIE was able to see conditions of the bolts and scan through a set of beams at 12th bent. The BIE asked for a lined-up camera position to be able to see shifts of bearings. The BIE noted that the progress was very similar to regular inspection.

In 5th flight 9:18 am-9:28 am, zooming and angle changing were effective. The BIE was able to scan through beams within an average of three to four minutes if there was no major issue observed. By this flight, the UAS was over the vegetation. The BIE was able to identify spalling easily. As a note, the pilot did not show any concern or stress for aircraft safety in order not to intervene in the inspection. This was a critical relationship or degree of independence between the pilot and the controller.

On 6th flight 9:30 am-9:40 am, the BIE started to check the north side of 12th bent caps. Hairline cracks of 4 to 6-inch on different beams. Loosed bolts and rust bleeding were detected.

During 7th flight 9:49 am-9:58 am, UAS controllers' weights observed to be an issue similar to after 1.5 hours. From human factors, lining that supports and causes less stress to pilot and BIE is beneficial. The BIE was at 13th bent. No anchor bolts were observed (figure 5.24). This would require BIE to check plans. Thus, having electronic documents available could be beneficial. Finding angles to see loose bolts at this point was easy for the BIE as well as guiding the pilot to correct angles. Lining up to see bearing pad shifts were problematic under the bridge. On the sides, due to lighting, this was no issue. Lighting on the UAS might help. RTK correction earlier recognized to yield better flight during this one. Controller batteries were also changed after this flight.

Figure 5.24: Anchor bolt not tightened down.

In 8th flight 10:06 am-10:16 am, the team was at the south side of the 13th bent. Straight looks were bad and not comfortable. Closer views and angles recognized to improve this, however, the issue may require to develop a methodology to overcome. Spalls on the key edges were detected. Coordination of a specific angle was done to see possible bulging. Hairline map cracks were detected. The BIE's control over the camera at this point was smooth with no issues. The BIE also spent entire flight on this side of the beam as spalling and hairline map cracks were detected on different beams.

During 9th flight 10:20 am-10:29 am, the BIE noted that the issue of not able to see shifts under the bridge bearings was critical. The BIE was able to see minor north shifts on the outside bearing pads where it was argued that might be due to temperature. The BIE at this point was at 13th bent's north side.

In 10th flight 10:32 am-10:43 am, the BIE thoroughly scanned 13th bent's north side. A very small glitch on the connection was observed. Line of spalling, shrinkage cracking at the end of a beam, and minor shift on the side bearing pad was observed (figure 5.25).

Figure 5.25: Minor spalling observed with a drone.

For 11th flight 10:46 am-10:56 am, the team re-positioned between 13th and 14th bents and 15th bent of earth connection. Northside of 13 and the diaphragm between 13th and 14th bents were inspected.

During 12th, 13th, and 14th flights, 11:00 am-11:10 am, 11:14 am-11:25 am, and 11:30 am-11:35 am, both sides of the diaphragm and all connection bolts were scanned. Both sides of the 14th bent, outside connection bolts, outside bearings, diaphragm, and 15th bent straight ahead check were performed during this flight. During the 14th flight, the BIE checked over the deck of the bridge. He was able to see the cracking. He was able to zoom in to be able to see interesting checkpoints.

At the end of the experiment, it was pointed that a drone would not replace a detailed in-person inspection, however, the benefit would be for off years and quick checks and inspections. The BIE noted that inspection help would be enormous for concrete bridges, however, woodpile bridged would require sound checks. It was noted that it would be very beneficial if cracks over the deck could be calculated. Almost everything was seen except for some angles. It was noted that it would be beneficial to get closer with a smaller and caged aircraft. Zooming in such a case would be an issue. It was confirmed that UAS would help more than 50% of the bridge inspections. Clear policies about the UAS use need to be prepared with guidelines.

5.3 Remote-Live Stream Bridge Inspection

As a secondary experiment, the researchers conducted a proof of concept study of the possibility of inspecting a bridge with the BIE located off-site on October 2nd, 2019 (figure 5.26). The remote inspection experiment was very similar to the experiments previously described. The crew was made up of a pilot who commanded the aircraft, a co-pilot who controlled the camera and a third person who replaced batteries and managed the logistics of the site (figure 5.27). The BIE was located at their home office approximately 30 miles away (figure 5.28). The flight crew live-streamed the video using two different apps; Flighthub and Kittyhawk. The flight crew and BIE communicated by phone or through the app. The test bridge used in the previous experiment had insufficient cellular service to live stream the video so a similar bridge in an area with better coverage was selected (figure 5.29 and 5.30). The construction type of the bridge was the same and it also had two lanes of travel.

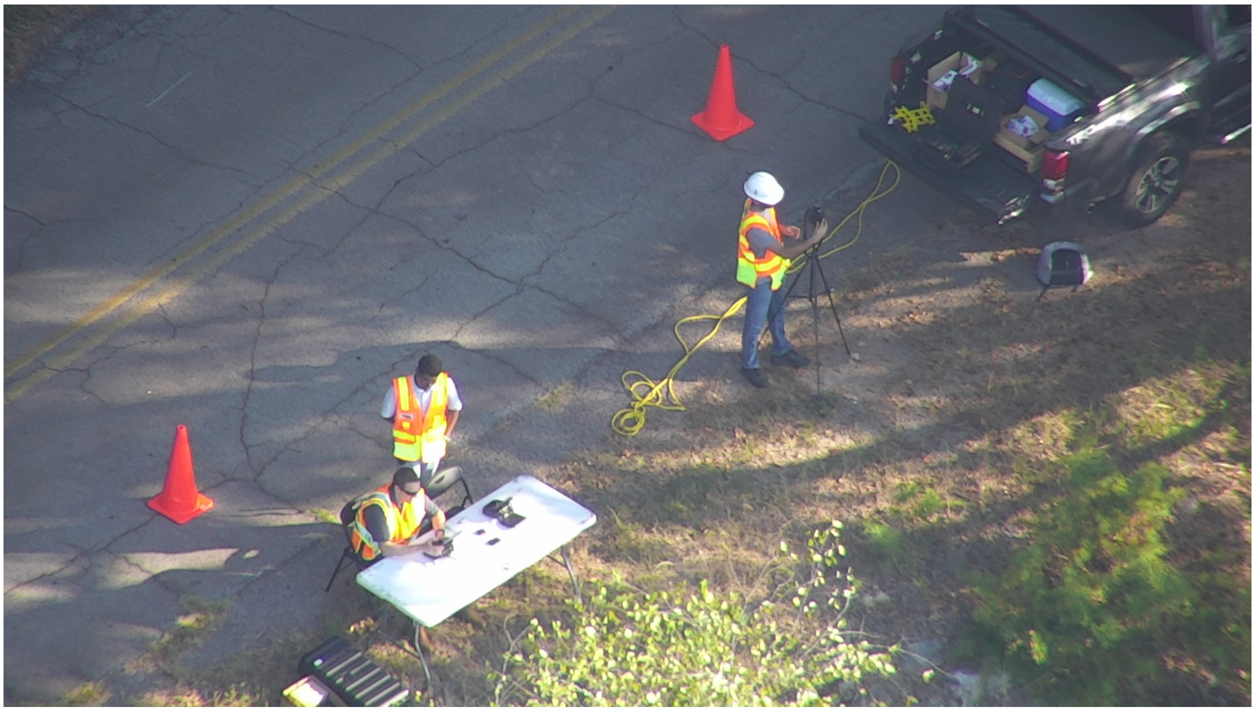


Figure 5.26: Remote BIE setup.

Figure 5.27: Remote inspection flight crew.

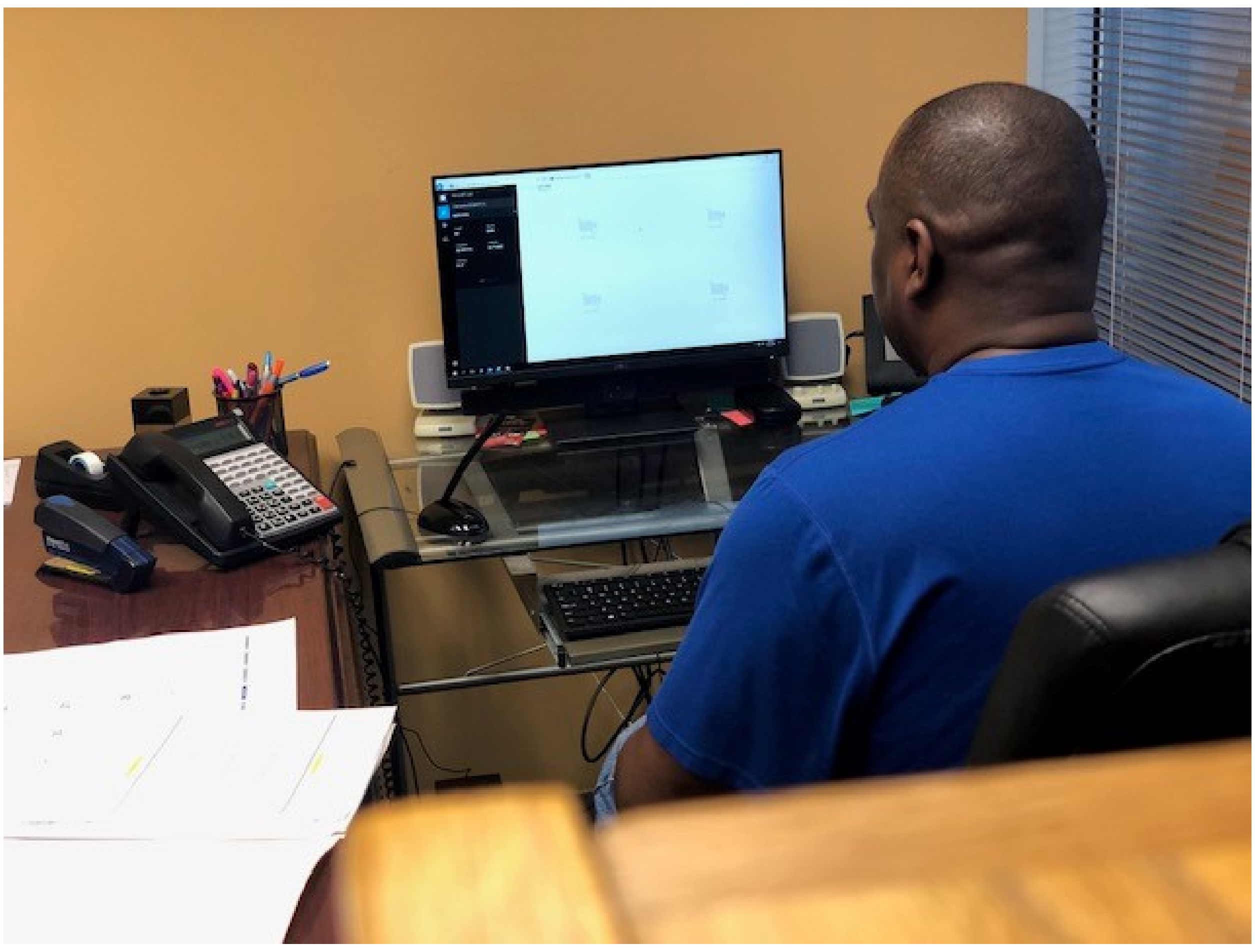


Figure 5.28: Remote BIE at a workstation.

Figure 5.29: Remote test bridge #1.

Figure 5.30: Remote test bridge #2.

The researchers experimented with two separate live stream apps which largely performed the same live-stream function; however, each had several adaptations that were beneficial for remote inspections. Kittyhawk is a third-party app that is constructed to mirror the look of the manufacturer's (DJI) flight control app. The latency between when the image was taken to when it was displayed on the BIE's screen was approximately 2 seconds. The researchers found that if the latency extended beyond 5 seconds it significantly impacted the efficiency of the inspection. It also allowed for two-way communication between the pilot and BIE directly through the app. This was a very convenient option as the flight crew did not need to have an additional distraction of calling through their phones. Kittyhawk was a third party app however and several functions from the manufacturer's flight app were not perfectly reproduced. Flighthub is produced by DJI who is also the manufacture of the aircraft. As this app was produced by the manufacturer, none of the functionality of the aircraft was lost during the live stream operation. The app allows for the "frames per minute" to be adjusted incrementally from 1 -100%. This was a valued feature of the app as it allows us to customize the broadcast speed to align with data connectivity strength. Flighthub allowed for one way communication from the controller out to the live stream viewer. Having two-way communication is a feature that would have been used if available. Anecdotally, the image quality from Flighthub seemed to be improved over Kittyhawk but this was not measured.

After the experiment, the onsite flight crew and the remote BIE felt that this was a valuable tool. They believe that this technology can be used to inspect bridges successfully with similar limitations as described in experiments one and two. Inspecting bridges remotely added additional complications to the process, however. These complications include sufficient connectivity to stream the video, latency in video and voice command and the use of additional technology that is not completely reliable.

5.4 Discussion

The purpose of this study was to evaluate how effective UAS can be as a tool to assist the SCDOT with bridge inspections. The overarching opinion of the researchers and the DOT BIEs was that drone technology is a valuable tool to support the process but was not a complete replacement for in-person inspections. UAS could, however, be used to reduce the length of use of UBITs, made documentation more convenient and reduced the safety hazard to the inspectors. The sections to follow will elaborate on the specific benefits, cost savings and limitations of incorporating drones into bridge inspection workflows using the Bates Bridge experiments as a test case.

5.4.1 Advantages of Drone Technology

The overall opinion of the BIEs and researchers of incorporating drone technology was positive. The majority of the inspection points (91%) could be observed with a drone equipped with a 30X zoom sensor. The UAS in the experiment provided a much more convenient way of capturing images and documenting the condition of the bridge than with traditional methods. A key advantage of drone deployment is the reduced need for a UBIT. UBIT often requires closing a lane of traffic and placing BIEs in harm's way. This was the case with the Bates Bridge test site. Operating a UAS can be done away from traffic and be nearly invisible to the traveling public. With the experiments conducted, the time needed to conduct the inspection with the drone was equivalent to that of traditional methods. However, it is important to note the UAS inspection speed increased throughout the inspection and that as this was the first time the BIEs had used the technology, as it becomes more commonplace, UAS inspections will likely be more time-efficient. Inspections using a UAS to augment in-person inspections reduced the length of time need for the UBIT, were safer and had improved documentation than with traditional methods alone.

5.4.2 Cost Comparison

As previously stated, this study did not find that UAS could replace UBIT entirely; however, it could significantly reduce the time they were needed. With experiments 1 and 2 at the Bates Bridge test site, both BIE were able to sufficiently observe 91% of the inspection points identified on the traditional bridge inspection report. The inspection points that could not be observed were primarily the bearing pads above the column caps at the bents (Figure 5.20 and 5.21). To further evaluate the use of this technology, a cost-saving analysis was conducted.

The researchers participated in the traditional inspection of the Bates Bridge and documented the resources needed to complete it. The BIE team for the SCDOT in District 7 was made of three inspection engineers. The Bates Bridge has two lanes (one in each direction). One of the lanes was required to be shut down in order to stage the UBIT (figure 5.31). This necessitated the use of six traffic control workers to safely coordinate alternating flows of traffic on a single lane. Traffic control also required two illuminated signs, six stationary signs, and approximately 75 cones. A crash attenuator trailer was staged behind the UBIT. Additionally, because the bridge was located over a waterway, a boat and operator were deployed for emergency water evaluations. The inspection started at approximately 8:00 am and finished at 5:00 pm for an 8-hour workday. A summary of the approximate costs is provided in table 5.1. The unit costs used were from published state DOT average costs databases and when not available RS Means by Gordian. The estimated cost to conduct this inspection using traditional methods was $5,242.

Figure 5.31: Lane closure of Bates Bridge.

Table 5.1: Estimated cost of a traditional inspection of the Bates Bridge

Cost Item	Quantity	Duration (hours)	Unit Cost	Cost
Bridge Inspection Engineer	3	8	$ 53.40	$ 1,281.60
Traffic Control Worker	6	8	$ 20.55	$ 986.38
Safety Spotter / Boat Operator	1	8	$ 22.55	$ 180.40
Under Bridge Inspection Truck	1	8	$ 298.60	$ 2,388.82
Traffic Control Signs (PCMS)	2	8	$ 3.77	$ 60.28
Traffic Control Signs	6	8	$ 0.05	$ 2.28
Boat	1	8	$ 6.22	$ 49.78
Crash Attenuator Trailer	1	8	$ 33.19	$ 265.50
Cones	75	8	$ 0.05	$ 27.00
Total Costs				$ 5,242.03

To assess the savings a UAS could provide, several assumptions need to be made. As determined in experiment #1 and #2, not all inspections points could be seen with the UAS so even if a drone was deployed, a UBIT would still be needed; albeit for a shortened period of time. It was not practical to time how long it would take to inspect only the inspection points that could not be seen (approximately 9% of the inspection points) so a professional judgment was made. It took approximately eight hours to inspect the bridge using traditional methods, so the researchers are assuming that if you remove 91% of the inspection points, the remaining 9% could be inspected with the UBIT in four hours. This includes time to mobilize, demobilize and inspect under each bent. It is also assumed that once the unfamiliarity of the UAS and initial instruction time is removed, the inspection of the 91% of the inspection points could be observed with the drone in 8 hours. Essentially, the overall inspection time would remain the same, but the equipment and traffic management resources would be reduced by half. The estimated cost to inspect the Bates Bridge with the UAS is $3,802 (table 5.2). This is a savings of approximately $1,440 for a single bridge.

Table 5.2: Estimated Cost of a UAS augmented inspection of the Bates Bridge

Cost Item	Quantity	Duration (hours)	Unit Cost	Cost
Bridge Inspection Engineer	3	8	$ 53.40	$ 1,281.60
Traffic Control Worker	6	4	$ 20.55	$ 493.19
Safety Spotter / Boat Operator	1	4	$ 22.55	$ 90.20
Under Bridge Inspection Truck	1	4	$ 298.60	$ 1,194.41
Illuminate Signs	2	4	$ 3.77	$ 30.14
Traffic Control Signs	6	4	$ 0.05	$ 1.14
Boat	1	4	$ 6.22	$ 24.89
Crash Attenuator Trailer	1	4	$ 33.19	$ 132.75
Cones	75	4	$ 0.05	$ 13.50
Drone Rental (lump sum)	1	n/a	$ 450.00	$ 450.00
Safety Spotter / Visual Observer	1	4	$ 22.55	$ 90.20
Total Costs				$ 3,802.01

5.4.3 Challenges of Drone Technology With Bridge Inspections

Despite the advantages, there are still several significant limitations of the technology that at present can only be met by in-person inspections. One example is that with traditional inspections, tactile contact with the structure is required. This includes chipping away loose concrete or rust and also sounding out material such as with woodpiles. Another limitation is the difficulty in flying under bridges where GPS signals are blocked. When GPS is available, especially when an RTK ground station is used, commercially available UAS are able to hold a static position with very little drift even in the presence of wind. However, under a bridge, the GPS signal is lost and the aircraft is susceptible to drift. Onboard accelerometers and proximity sensors help stabile the system, but flight controls are challenging for even seasoned pilots. The researchers found however, that much of the inspection can be performed under and to the side of the bridge, where GPS signal can be established and can zoom and angle up to the underside of the bridge of interest. Taller bridges allow for a more aggressive angle improving the field of view. It was also observed that using lower-cost drones may be more advantageous than higher performance rigs with zoom cameras for under-bridge inspections. Lower-cost units would need to fly closer to observe the bridge sufficiently increasing the risk of collision; however, that risk is offset by the lower cost to replace the unit. Bridges with vegetation around them also limit the value to drone use. Even with GPS lock established, a small branch, which may not be detected by onboard sensors or visible in the pilot's first-person view screen could cause a crash if it collides with the propellers.

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