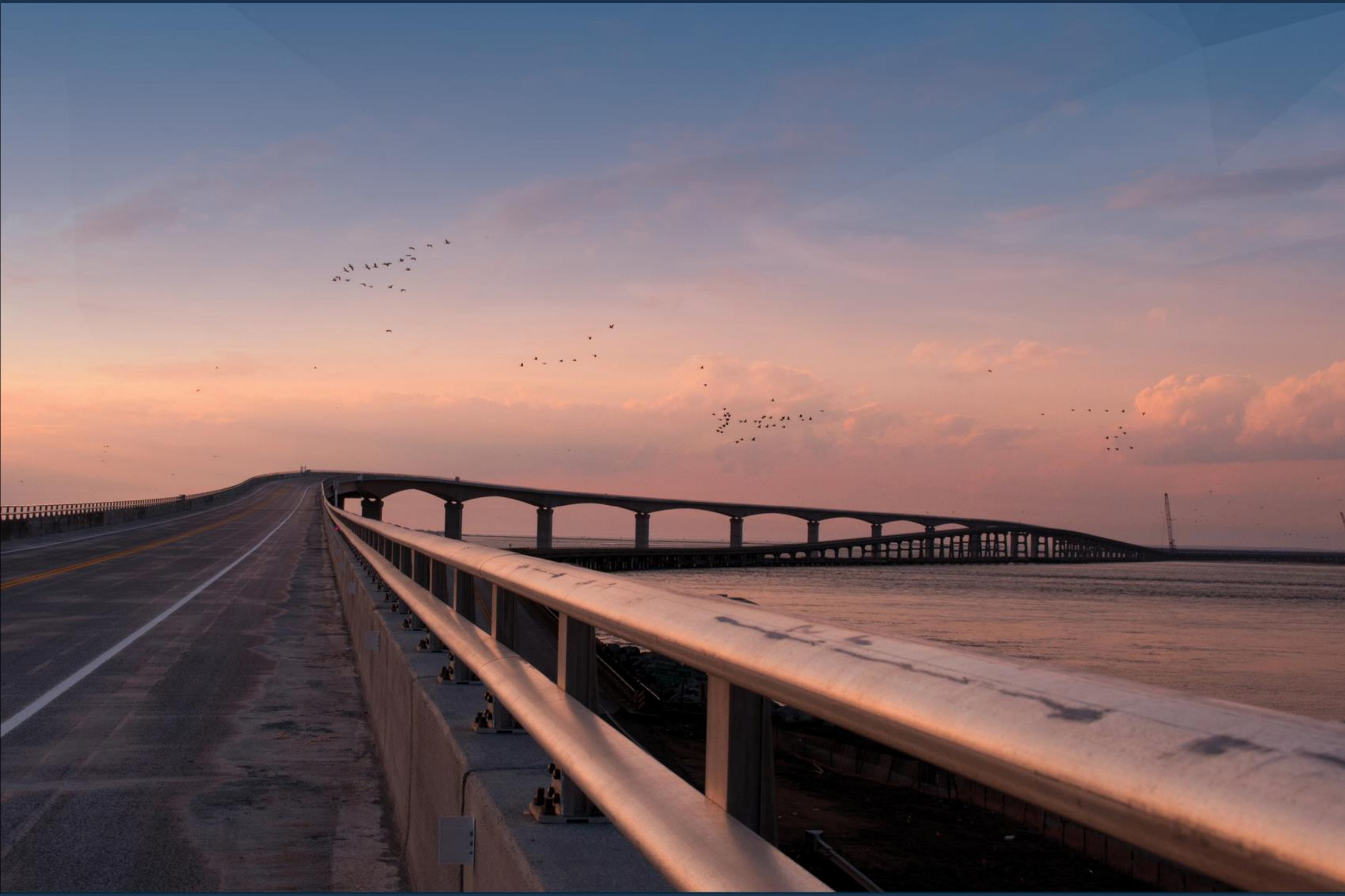
Workflows, Implementation Tools, and Guidance for Efficient UAV-enabled Bridge Inspection



NCDOT Project RP2022-10
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June 2024

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RESEARCH & DEVELOPMENT

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16. Abstract

This project developed workflows and tools to advance the implementation and adoption of UASs to support bridge inspection practices. A series of workflows was developed to guide inspection personnel when conducting UAS-enabled bridge inspections, and guidance was prepared to assist agencies in the identification of bridge and site characteristics that should be considered when determining the suitability of a bridge for UAS-enabled bridge inspection. Workflows developed as a part of this project adhere to FHWA regulations, NCDOT regulations, and UAS operation requirements. The workflows align with FHWA inspection requirements, the Bridge Inspection Reference Manual (BIRM), and the NCDOT Structures Management Unit (SMU) Inspection Manual. The NCDOT-developed Wearable Inspection and Grading Information Network System (WIGINS) software, historically used to support bridge inspection data collection and archiving, was also used to inform the development of the UAS-enabled bridge inspection workflows. This work supports data entry into the WIGINS Element software, as currently used by inspectors in the field and office.

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    - Traffic Control and Access Equipment Operators from Span 1 and Anderson Under Bridge.

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EXECUTIVE SUMMARY

The goal of this research was to develop workflows and tools to advance the implementation and adoption of UASs to support bridge inspection practices. This research resulted in the development of a series of workflows to guide inspection personnel when conducting UAS-enabled bridge inspections, and the identification of bridge and site characteristics that should be considered when determining the suitability of a bridge for UAS-enabled bridge inspection.

Workflows developed as a part of this project adhere to FHWA regulations, NCDOT regulations, and UAS operation requirements. The workflows align with the FHWA bridge inspection requirements, the Bridge Inspection Reference Manual (BIRM), and the NCDOT Structures Management Unit (SMU) Inspection Manual. The NCDOT developed Wearable Inspection and Grading Information Network System (WIGINS) software, historically used to support bridge inspection data collection and archiving, which was also used to inform development of the UAS-enabled bridge inspection workflows. This work supports data entry into the WIGINS Element software, as currently used by inspectors in the field and office.

In summary, the following objectives were achieved in this project:

1- Understand the current UAS-enabled bridge inspection regulations, procedures, and capabilities.

2- Develop UAS-enabled bridge inspection workflows customized to NCDOT's bridge inspection and data recording practices that can serve as preliminary guidance as NCDOT moves towards more broad use of UAS-enabled inspections.

3- Implement the developed workflows in the field, allowing NCDOT bridge inspectors and UAS pilots to review and critique the workflows for further refinement.

4- Develop a tool for assessing the logistic and time estimation for the pre-inspection stage of UAS-enabled bridge inspection.

UAS-enabled bridge inspection workflows created as part of this work are optimized for use by NCDOT inspection personnel but could be adapted by other agencies as well. These workflows should serve as tools to enable UAS-enabled inspection by personnel that are new to the integration of UASs in their routine bridge inspection process. The identification of bridge characteristics along with their corresponding quantitative and qualitative limits that would impact a bridge's suitability for UAS-enabled bridge inspection will also assist the NCDOT and their PEFs in advancing UAS-enabled bridge inspection statewide.

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1 INTRODUCTION AND RESEARCH OBJECTIVES

1.1 Introduction

Bridge inspections are required by the Federal Highway Administration (FHWA) via the National Bridge Inspection Standards (NBIS) in Chapter G, Part 650, subpart C (FHWA 2022). The FHWA requires all bridges to be inspected periodically. The different types of inspections categorized by the FHWA include initial inspections, routine inspections, underwater inspections, in-depth inspections, damage inspections, and special inspections (FHWA 2022). Bridge inspections can also be conducted for different purposes such as maintenance, construction, and emergency damages, in order to ensure the structural integrity of the bridges. The different types of inspections are associated with different requirements for intervals and processes.

Performing a bridge inspection is often costly and time consuming for bridge owners, who are typically state highway agencies, municipalities, and other entities. In the state of North Carolina, there are over 13,500 bridges that the North Carolina Department of Transportation (NCDOT) is responsible for maintaining (NCDOT 2021). The average cost to inspect a bridge in the United States ranges from $4,500 to $10,000, and the average time to complete an inspection range from 1 to 3 days (Zulfiqar et al. 2014). In many cases, the majority of the inspection time is dedicated to setting up traffic control and providing access for inspectors to observe and inspect the elements of the bridge that require such attention. The introduction of unmanned aerial systems (UAS) into bridge inspection helps bridge inspectors to visually inspect and photograph the structure and surrounding areas swiftly with a reduced number of support personnel and equipment, often enabling faster inspection times and lower inspection costs (Banks et al. 2018; Cheyne et al. 2019). UASs are also very portable and have become reasonably affordable for local agencies and private engineering firms (PEFs) to access.

However, the implementation of UASs is still in its infancy in the bridge inspection sector. Although the FHWA has recently published guidance on the use of UAS in bridge inspections (Neubauer et al. 2021), the actual implementation of UAS-enabled bridge inspection by state highway agencies is still a work in progress. Widespread implementation faces challenges, including rigorous Federal Aviation Administration (FAA) certifications for inspectors and the need to establish inspection guidelines when using UASs (Wells and Barritt 2015, Wells and Lovelace 2017). One of the key current challenges impeding the implementation of UAS-enabled bridge inspection is the lack of guidance on developing a practical workflow (NCDOT 2021).

There are many entities working to provide guidance and support to bridge engineers and inspectors on the incorporation of UASs into typical bridge inspection procedures. However, many recent studies have primarily focused on drone technology and the data processing aspects of the operation (further described in Chapter 2). The development of a UAS-enabled bridge inspection workflow, or a series of workflows tailored to the characteristics of groups of typical bridges, which incorporates both bridge inspection standards and UAS operating procedures would help support the implementation of UAS-enabled bridge inspection in the state of North Carolina and potentially in other states and municipalities. Workflows developed as part of this research aim to be inspection-centered workflows that meet not only FHWA bridge inspection regulations, but also NCDOT bridge inspection requirements.

1.2 Research Objectives

The goal of this research was to develop a series of UAS-enabled bridge inspection workflows to support NCDOT field inspection personnel. Identification of bridge characteristics to support the selection of suitable bridges for UAS-enabled bridge inspection was also performed. The end goal was to develop UAS-enabled bridge inspection workflows tailored for use on specific types of structures, with companion guidance that supports inspection personnel in the field while conducting bridge inspections.

Workflows developed as a part of this project adhere to current FHWA regulations, NCDOT regulations, and UAS operation requirements. The workflows align with FHWA bridge inspection requirements, the Bridge Inspection Reference Manual (BIRM), as well as the NCDOT Structures Management Unit (SMU) Inspection Manual. The NCDOT developed Wearable Inspection and Grading Information Network System (WIGINS) software, historically used to support bridge inspection data collection and archiving, which was also used to inform the development of the UAS-enabled bridge inspection workflows. This work supports data entry into the WIGINS Element software, as currently used by inspectors in the field and office.

There were three objectives of this research. The first objective was to understand the UAS-enabled bridge inspection regulations, procedures, and capabilities. The second objective was the development of preliminary UAS-enabled bridge inspection workflows customized to NCDOT's bridge inspection and data recording practices. The third objective includes the implementation of the developed workflows in the field, allowing NCDOT bridge inspectors and UAS pilots to review and critique the workflows for further refinement. Guidance and tools to support the implementation of UASs into NCDOT's practices were also developed.

UAS-enabled bridge inspection workflows created as part of this work were optimized for NCDOT inspection personnel use but could be adapted by other agencies as well. These workflows should serve as tools to enable UAS-enabled inspection by personnel that are new to the integration of UASs in their routine bridge inspection process. The identification of bridge characteristics along with their corresponding quantitative and qualitative limits that would impact a bridge's suitability for UAS-enabled bridge inspection will also assist the NCDOT and their PEFs in advancing UAS-enabled bridge inspection statewide. Guidance and tools to support the broader use of UAS in bridge inspections and implementation of UAS into standard practice are tailored to NCDOT's approaches but could be readily modified to be used by other agencies, if interested.

2 SUMMARY OF KEY LITERATURE FINDINGS: IDENTIFYING BRIDGE INSPECTION CHALLENGES AND OPPORTUNITIES

2.1 Bridge Inspection Requirements

Bridges are vital to the United States transportation system. A total of over 615,000 bridges are currently maintained by various U.S. agencies and municipalities (FHWA 2022). Each bridge serves the important responsibility of carrying traffic over water, traffic, land feature, and/or railroad. The collapse of the Silver Bridge at the Ohio and West Virginia border in 1967 sparked Congress's desire to create the Federal Highway Act of 1968, which required the Secretary of Transportation to develop a standard for bridge inspections (Ryan et al. 2012). The NBIS, the NCDOT Element Inspection Manual, and the NCDOT SMU Inspection Manual collectively provide bridge inspection guidance within the state of North Carolina.

To unify the inspection standards and procedures around the country, the FHWA established the National Bridge Inspection Standards, also known as the NBIS (FHWA 2022). The NBIS states that federal and state agencies are responsible for inspecting and reporting elemental components of all bridges to the Secretary of Transportation of the United States Department of Transportation (USDOT) on specific time intervals that depend on the type of inspection that the structure requires (FHWA 2022).

The FHWA is a branch under the USDOT that supports state and local governments in the design, construction, and maintenance of the public highway system (FHWA 2022). Bridges and other structures, such as culverts and overhead signs, are parts of the public highway systems and are inspected per the NBIS regulations (AASHTO 2010). The FHWA recognizes that bridge components are often sophisticated and have diverse physical and site characteristics, including a wide variety of lengths, spans, materials, structural design types, geometric configurations, and traffic characteristics, among other things. The FHWA Recording and Coding Guide for the Structural Inventory and Appraisal of the Nation's Bridges, commonly known as the Recording and Coding Guide, historically provided the list of description items that are expected to be recorded for a bridge. Detailed descriptions of every element of the bridge, or "items," can be found in the Recording and Coding Guide, along with explanations on how the items should be coded (FHWA 1995; AASHTO 2010). This has recently been replaced by the FHWA's Specifications for the National Bridge Inventory (FHWA 2022).

Within North Carolina, the NCDOT oversees the inspection, load capacity analysis, inventory, and administration of maintenance policies and procedures for all structures on the public highway system (NCDOT 2017). Besides inspecting the items listed in the Recording and Coding Guide (now the SNBI), the NCDOT also has its own "special elements" to inspect. These additional special elements are listed in the NCDOT Element Inspection Manual (NCDOT 2017). Similar to the FHWA's Recording and Coding Guide, the NCDOT Element Inspection Manual provides a detailed breakdown of how to inspect these special NCDOT bridge elements. The NCDOT's Element Inspection Manual provides guidance for the state's bridge inspection operations ranging from general condition ratings such as the superstructures, to the rating of individual elements such as the joints (NCDOT 2017). The NCDOT developed the Element Inspection Manual to ensure compliance with federal standards and to establish the state's expectations for bridge inspection (FHWA 2022; NCDOT 2017).

To communicate the bridge inspection policies and procedures adopted by the NCDOT to inspection personnel and PEFs, the NCDOT created the SMU Inspection Manual to provide guidance on those topics (NCDOT 2018). The types of inspections covered by the SMU Inspection Manual include initial inspections, routine inspections, underwater inspections, fracture critical inspections, in-depth inspections, special inspections, damage inspections, and bridge maintenance supervisor inspections. The fracture critical inspection that the NCDOT conducts is equivalent to the nonredundant tension steel member (NTSM) inspection required by the FHWA (NCDOT 2018; FHWA 2022). Recently, the term "fracture critical" has been replaced by "non-redundant steel tension member," or NSTM.

2.1.1 National Bridge Inspection Standards

The National Bridge Inspection Standards (NBIS) was established by the FHWA to provide guidelines on how state and local transportation agencies should conduct bridge inspection, and how to submit the relevant data to the FHWA for organizing and tracking purposes (FHWA 2022). In 1971, the NBIS was established in response to the collapse of the Silver Bridge in Point Pleasant, WV (Ryan et al. 2012). Prior to the NBIS, there were no guidelines established by the federal government to dictate bridge inspection and management practices in the United States.

The latest edition, the NBIS 2022 Final Rule, provided updated rules and regulations for bridge inspections (FHWA 2022). Certain bridges that meet all qualifications stated in the updated rule may undergo routine inspection on longer intervals than the typical once per every two years interval that has been mandated for bridges in the past. The conditions of the bridges and related actions are required to be reported to the FHWA (FHWA 2022).

2.1.1.1 Bridge Inspection Reference Manual

To aid field offices and personnel in the performance and documentation of bridge inspections, the FHWA created the Bridge Inspection Reference Manual (BIRM) (Ryan et al. 2022). The BIRM condenses the NBIS information for practicality purposes, thus often becoming the “go-to” resource for inspection personnel.

The BIRM includes topics such as equipment necessary for bridge inspection, bridge inspection safety precautions, inspection methods for different components of the bridge, and bridge inspection recording. The BIRM acts as the “instruction manual” for detailed bridge inspection quality control and quality assurance procedures provided by the FHWA (FHWA 2022).

2.1.2 NCDOT Element Inspection

The FHWA grants state and local agencies the ability to customize the definition of the elements according to the NBIS (FHWA 2022). Since the end goal of the NBIS is to ensure consistency in bridge inspection practices throughout the United States, the NBIS allows states and local agencies to expand their own bridge elements based on agency needs and preferences (NCDOT 2017). The additional bridge elements introduced by individual states expand upon the AASHTO Guide for Commonly Recognized Structural Elements (NCDOT 2017). Based on the NCDOT’s Bridge Management System (BMS), the NCDOT expanded its bridge element bank and called it Agency Defined Elements (ADE) (NCDOT 2017). The comprehensive list of elements that the NCDOT inspects can be found in the NCDOT Manual for Bridge Element Inspection (NCDOT 2017). Examples of NCDOT-specific bridge elements are diaphragms, slope protection components, truss members, reinforced concrete deck, prestressed concrete girder top flange, timber bridge railing, masonry bridge railing, steel truss, elastomeric bearings, and other items. The NCDOT elements are generally more specific in terms of component and material when compared to those of the National Bridge Elements.

There are two sets of element lists that the FHWA requires state and local agencies to abide by when compiling their own bridge element breakdowns, the Bridge Management Elements (BME) and the National Bridge Elements (NBE) (FHWA 2022). The NCDOT follows the rating system set by the FHWA to rate the conditions of the elements (NDOT 2017) and the SNBI (FHWA 2022).

2.1.2.1 Structures Management Unit Inspection Manual

The SMU Inspection Manual was developed to help field inspectors of the NCDOT and PEFs supporting the NCDOT conduct bridge inspection, analysis, and inventory (NCDOT 2018). The SMU Inspection Manual details NCDOT standards for bridge inspection for personnel who are in either quality assurance or quality control roles. This manual is based on the FHWA NBIS as well as the NCDOT Element Inspection Manual, thus being a compilation of both federal and state-level bridge inspection requirements (NCDOT 2017; NCDOT 2018). Another important type of information provided in the SMU Inspection Manual is the list of categories of different bridge inspections and frequencies, along with the associated requirements. From routine inspections that occur once every 24 months to underwater inspections no less than once every 48 months, the SMU Inspection Manual provides thorough requirements on the inspection activities that should be performed based on the structure type, as well as reporting requirements (NCDOT 2018).

Understanding the different types of inspections required by the NCDOT is vital since different inspection methods apply to different scenarios. The seven types of bridge inspections are as follows:

1) Initial Inspections
2) Routine Inspections
3) Underwater Inspections
4) Fracture Critical Inspections
5) In-depth Inspections
6) Special Inspections
7) Damage Inspections

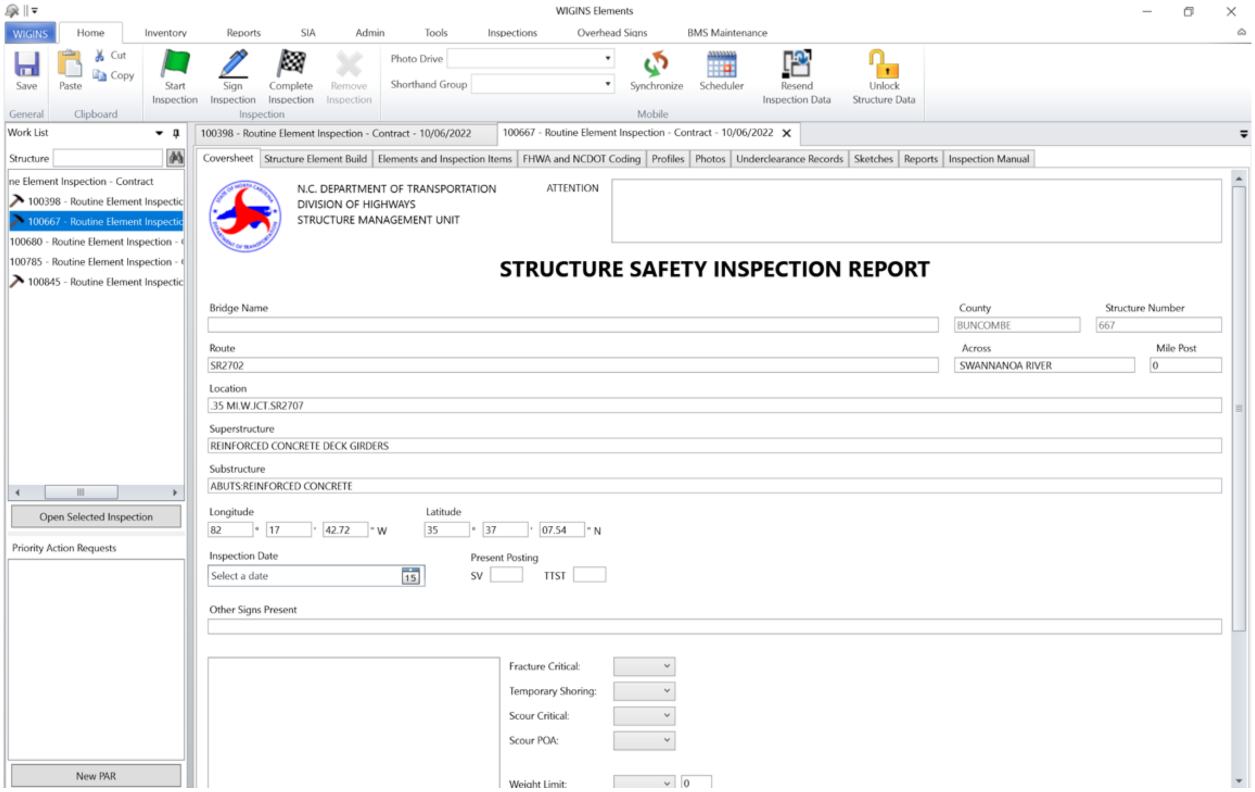
The different types of inspections typically require different inspection methods and intervals according to the SMU Inspection Manual and are aligned with the requirements stated in the NBIS (FHWA 2022). For example, a routine inspection could require less hands-on intensive inspection, while fracture critical inspection requires intensive hands-on inspection due to the type of structure that is being inspected and elevated risk to safety (NCDOT 2018). Some inspections are also focused on specific areas of the bridge, such as submerged components (underwater inspections) and areas damaged due to accidents, such as over-height vehicle collisions (damage inspections).

2.1.3 WIGINS Elements

WIGINS Elements was designed by former NCDOT employee Lin Wiggins to help autonomize the sorting of bridge data within the state of North Carolina. WIGINS can synchronize bridge inspection data throughout the state so that future inspection personnel can easily interpret and modify bridge data (NCDOT 2018). The development of the UAS-enabled bridge inspection workflow will heavily rely on the implementation of WIGINS since it is the central to the NCDOT bridge inspection process as well as the framework for record keeping and preparation of the required bridge inspection reports (NCDOT 2018).

One benefit of WIGINS Elements is the digitization of inspection data and the ease of populating inspection documents. The software allows the inspectors to record and save all inspection documents digitally, including inspection images. The digitization of inspection documents grants inspectors the ability to be paperless in the field which is also an advantage since paper recordkeeping sometimes becomes problematic in outdoor areas. A portable tablet computer is the only necessity during an inspection for the distress information input process into WIGINS Elements (NCDOT 2018), although some inspectors interviewed as part of this work still prefer to use paper notes. Inspectors using paper notes have often developed a notetaking system, however, that aligns with the WIGINS software for ease of data entry on site (e.g., in the vehicle after the inspection) or back at the office.

Another benefit that the WIGINS software provides is the streamlining of the documentation submission process. In the past, bridge inspectors would have to first take pictures and record in their notebooks detailed descriptions of the inspection notes, and then transfer all data online after arriving at their offices. With WIGINS Elements, data can be uploaded immediately onto the cloud upon the inspector's entry. The inspection data entry process is more efficient with the help of WIGINS Elements. If applicable, the NCDOT Central Office could be notified immediately through WIGINS Elements if there is a Priority Maintenance item discovered during the inspection to accelerate the determination of the maintenance need and scheduling a maintenance crew to perform maintenance on the structure (NCDOT 2018). Figure 2.1 depicts the cover sheet of an example structure file on WIGINS Elements. Figure 2.2 depicts the Structure Element Build of WIGINS Elements for the recording of structural dimension.



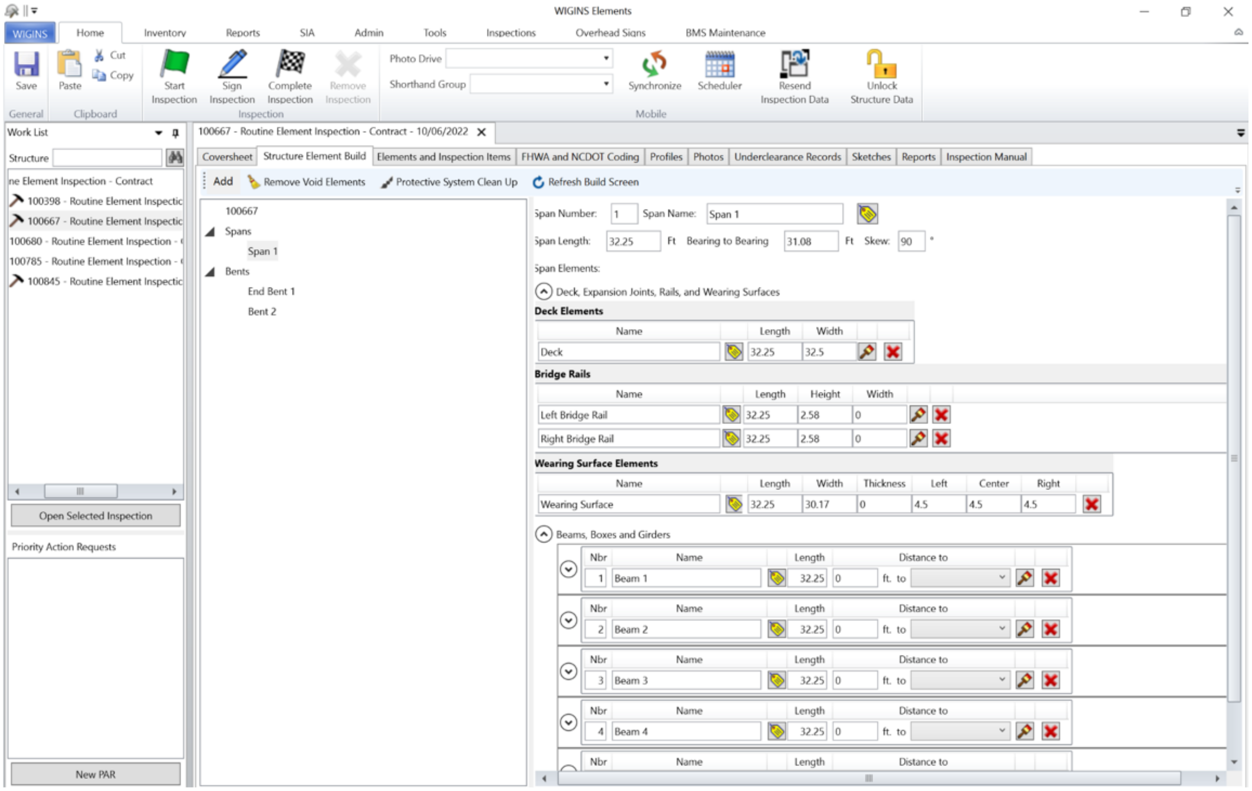
N.C. DEPARTMENT OF TRANSPORTATION
DIVISION OF HIGHWAYS
STRUCTURE MANAGEMENT UNIT

ATTENTION

STRUCTURE SAFETY INSPECTION REPORT

Bridge Name:
County: BUNCOMBE
Structure Number: 667
Route: SR2702
Across: SWANNANOA RIVER
Mile Post: 0
Location: .35 MI.W.JCT.SR2707
Superstructure: REINFORCED CONCRETE DECK GIRDERS
Substructure: ABUTS:REINFORCED CONCRETE
Longitude: 82 ° 17 ' 42.72 " W
Latitude: 35 ° 37 ' 07.54 " N
Inspection Date: Select a date
Present Posting: SV TTST
Other Signs Present:
Fracture Critical:
Temporary Shoring:
Scour Critical:
Scour POA:
Weight Limit: 0

Figure 2.1: Coversheet Tab (NCDOT 2022).



Span Number: 1 Span Name: Span 1

Span Length: 32.25 Ft Bearing to Bearing 31.08 Ft Skew: 90 °

Span Elements:

Deck, Expansion Joints, Rails, and Wearing Surfaces

Deck Elements

Name	Length	Width
Deck	32.25	32.5

Bridge Rails

Name	Length	Height	Width
Left Bridge Rail	32.25	2.58	0
Right Bridge Rail	32.25	2.58	0

Wearing Surface Elements

Name	Length	Width	Thickness	Left	Center	Right
Wearing Surface	32.25	30.17	0	4.5	4.5	4.5

Beams, Boxes and Girders

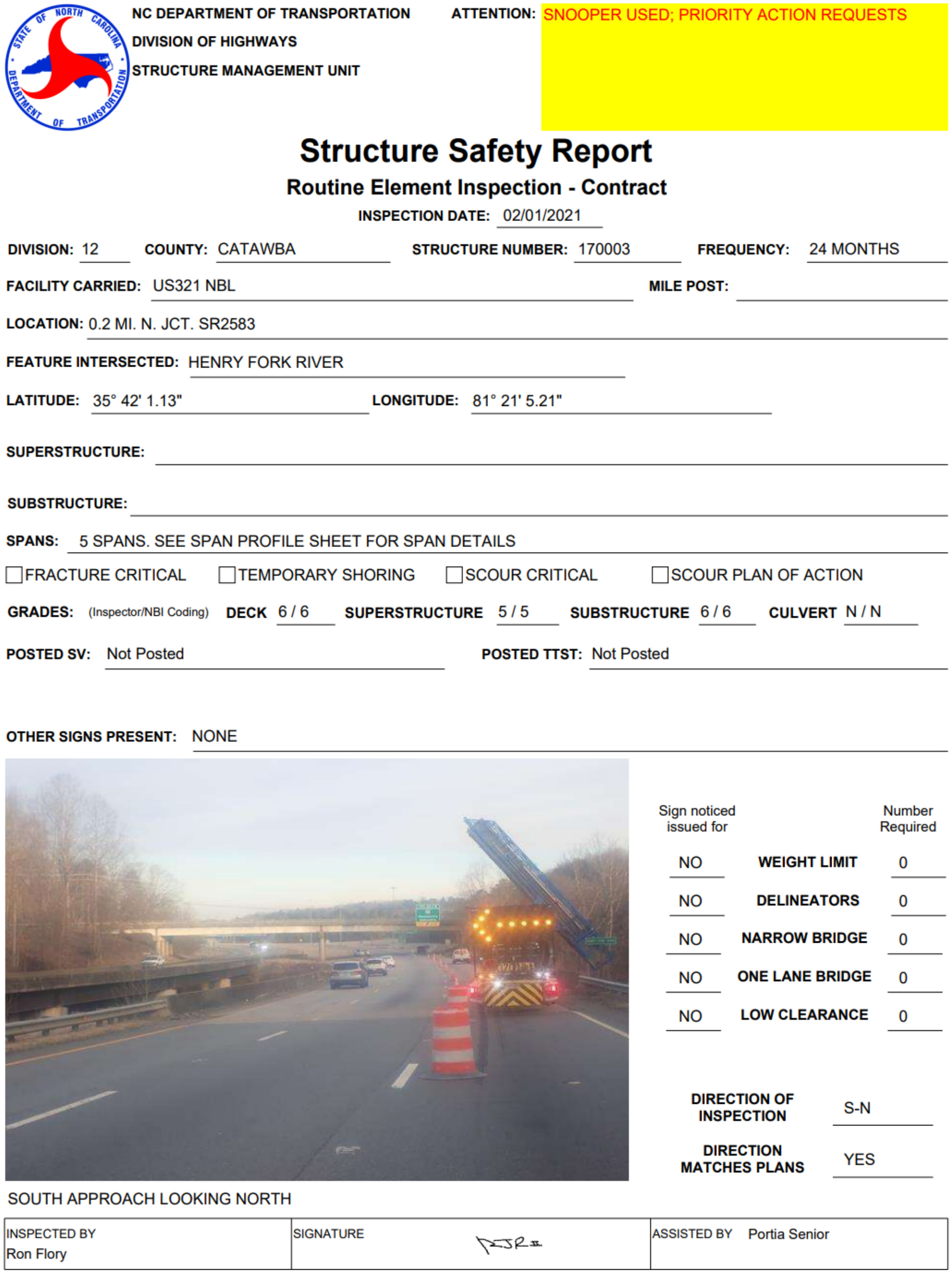
Nbr	Name	Length	Distance to
1	Beam 1	32.25	0 ft. to
2	Beam 2	32.25	0 ft. to
3	Beam 3	32.25	0 ft. to
4	Beam 4	32.25	0 ft. to

Figure 2.2: Structure Element Building Tab (NCDOT 2022).

The order in which the tabulated sections are presented in WIGINS corresponds to the order of data input by NCDOT bridge inspectors. The acknowledgment of this order provides insight into the development of the workflows since the workflows should be designed to fit current bridge inspection standard operating procedures. The WIGINS Elements software includes several major tabulated sections within a report, listed as follows:

1) Coversheet
2) Structure Element Build
3) Elements and Inspection Items
4) FHWA and NCDOT Coding
5) Profiles
6) Photos
7) Under clearance Records
8) Sketches
9) Reports
10) Inspection Manual

The Structure Safety Report concludes all bridge inspection findings and recordings for the most recent inspection operation. All required structural measurements such as bridge dimensions, as well as distress measurements such as crack quantification, can be found in the Structure Safety Report. The Structure Safety Report also provides information on action items that need to be performed to address issues at the structure. These action items include routine maintenance items, Priority Maintenance items, and Critical Findings (NCDOT 2018). Figure 2.3 depicts the title page of an example Structure Safety Report compiled for structure 170003 (NCDOT 2021).



NC DEPARTMENT OF TRANSPORTATION
DIVISION OF HIGHWAYS
STRUCTURE MANAGEMENT UNIT

ATTENTION: SNOOPER USED; PRIORITY ACTION REQUESTS

Structure Safety Report

Routine Element Inspection - Contract

INSPECTION DATE: 02/01/2021

DIVISION: 12 **COUNTY:** CATAWBA **STRUCTURE NUMBER:** 170003 **FREQUENCY:** 24 MONTHS

FACILITY CARRIED: US321 NBL **MILE POST:**

LOCATION: 0.2 MI. N. JCT. SR2583

FEATURE INTERSECTED: HENRY FORK RIVER

LATITUDE: 35° 42' 1.13" **LONGITUDE:** 81° 21' 5.21"

SUPERSTRUCTURE:

SUBSTRUCTURE:

SPANS: 5 SPANS. SEE SPAN PROFILE SHEET FOR SPAN DETAILS

☐FRACTURE CRITICAL ☐TEMPORARY SHORING ☐SCOUR CRITICAL ☐SCOUR PLAN OF ACTION

GRADES: (Inspector/NBI Coding) **DECK** 6 / 6 **SUPERSTRUCTURE** 5 / 5 **SUBSTRUCTURE** 6 / 6 **CULVERT** N / N

POSTED SV: Not Posted **POSTED TTST:** Not Posted

OTHER SIGNS PRESENT: NONE

Sign noticed issued for		Number Required
NO	**WEIGHT LIMIT**	0
NO	**DELINEATORS**	0
NO	**NARROW BRIDGE**	0
NO	**ONE LANE BRIDGE**	0
NO	**LOW CLEARANCE**	0

DIRECTION OF INSPECTION S-N

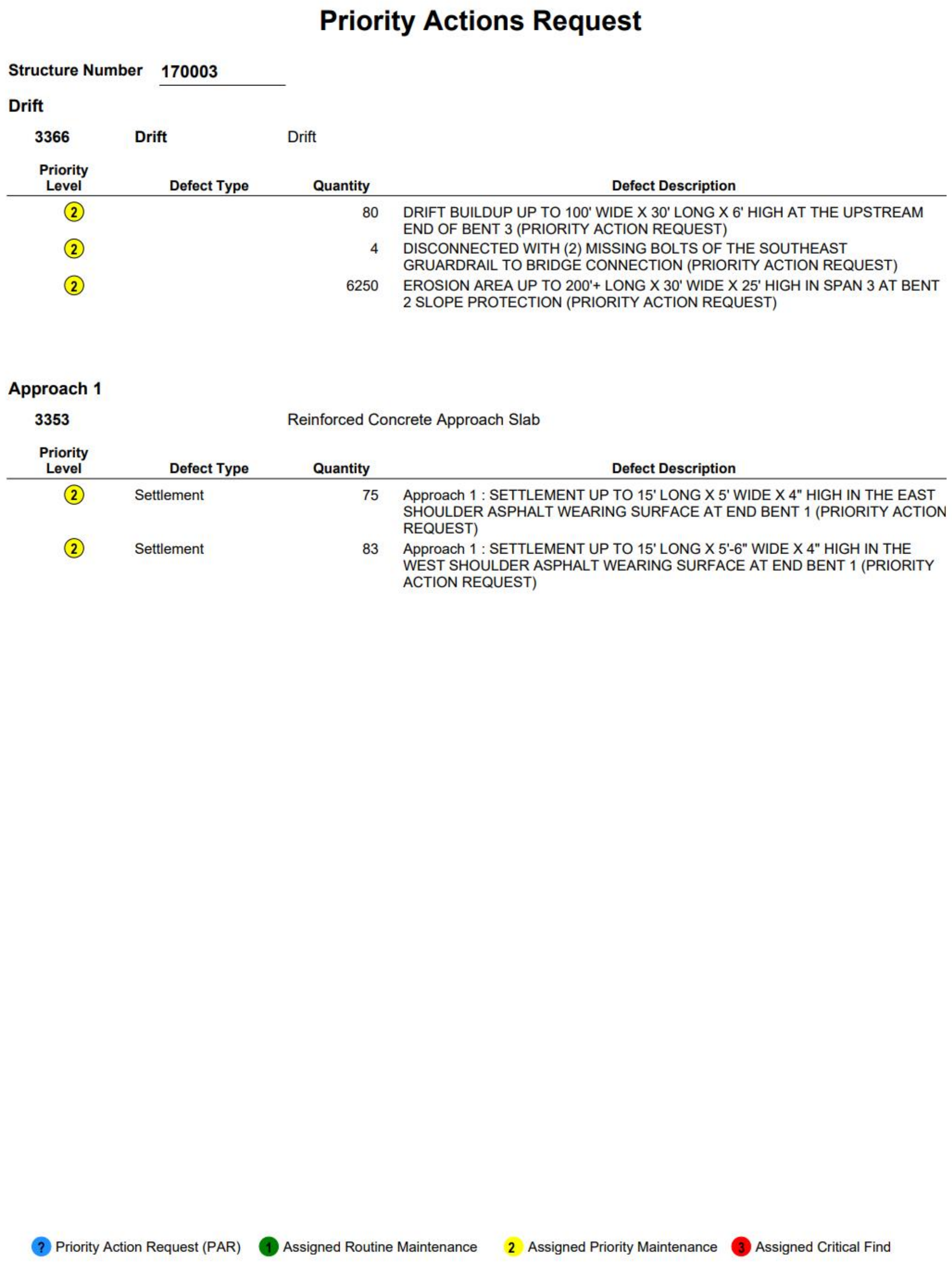
DIRECTION MATCHES PLANS YES

SOUTH APPROACH LOOKING NORTH

INSPECTED BY	SIGNATURE	ASSISTED BY
Ron Flory		Portia Senior

Figure 2.3: Location weather station mounted above the deck.

During the inspection, the inspector will submit one of the three action items depending on the condition of the distress. The severity of the distress depends on the material and is detailed in the SMU Inspection Manual (NCDOT 2018). If the inspection crew submits either a Priority Maintenance item or a Critical Finding, the NCDOT Central Office will be notified and handed the duty of reclassifying the distress. Reclassifying the distress includes verifying whether the distress falls under a routine maintenance item, Priority Maintenance item, or Critical Finding (NCDOT 2018). Figure 2.4 depicts the inspector requested maintenance items for structure 170003 on 2/1/2021 (NCDOT 2021).



Priority Actions Request

Structure Number 170003

Drift

3366 **Drift** Drift

Priority Level	Defect Type	Quantity	Defect Description
②		80	DRIFT BUILDUP UP TO 100' WIDE X 30' LONG X 6' HIGH AT THE UPSTREAM END OF BENT 3 (PRIORITY ACTION REQUEST)
②		4	DISCONNECTED WITH (2) MISSING BOLTS OF THE SOUTHEAST GRUARDRAIL TO BRIDGE CONNECTION (PRIORITY ACTION REQUEST)
②		6250	EROSION AREA UP TO 200'+ LONG X 30' WIDE X 25' HIGH IN SPAN 3 AT BENT 2 SLOPE PROTECTION (PRIORITY ACTION REQUEST)

Approach 1

3353 Reinforced Concrete Approach Slab

Priority Level	Defect Type	Quantity	Defect Description
②	Settlement	75	Approach 1 : SETTLEMENT UP TO 15' LONG X 5' WIDE X 4" HIGH IN THE EAST SHOULDER ASPHALT WEARING SURFACE AT END BENT 1 (PRIORITY ACTION REQUEST)
②	Settlement	83	Approach 1 : SETTLEMENT UP TO 15' LONG X 5'-6" WIDE X 4" HIGH IN THE WEST SHOULDER ASPHALT WEARING SURFACE AT END BENT 1 (PRIORITY ACTION REQUEST)

? Priority Action Request (PAR) ① Assigned Routine Maintenance ② Assigned Priority Maintenance ③ Assigned Critical Find

Figure 2.4: Location weather station mounted above the deck.

Some of the most important pieces of information included in the Structure Safety Report are the photographs taken. The NCDOT requires photographs to be taken during the inspection trip (NCDOT 2018). These photographs best serve the purpose of depicting and archiving the status of the distress and the overall condition of the bridge. Typical photographs taken during the inspection and included in the report are a series of required photographs that depict the condition of the bridges and pictures of the typical conditions and individual distresses. These required photographs include the following (NCDOT 2021):

- Approaches
- Profile
- Upstream and Downstream
- Guardrail
- Structure
- Inspection equipment

The detailed requirements for the photographs as well as bridge inspection practices required during the bridge inspection process can be found in WIGINS Element. The document within WIGINS Element, titled NCDOT Bridge Inspection Reference Guide, provides detailed guidance for inspectors on how to compile a Structure Safety Report via WIGINS Elements. This document serves as a useful guide for inspectors (in both the field and office) on the nuances of inspecting a bridge, data entry into WIGINS Element, and compiling a Structure Safety Report.

2.1.4 NCDOT Data Management for Structures

Through WIGINS, any NCDOT personnel who is given authorization may be able to access and manipulate the data shown on the Structure Safety Report. An advantage of having all data being linked to the cloud is that inspectors can update the information from different workplaces across the state, providing real-time updates on a particular structure’s data. Through WIGINS, the bridge inspection data can be compiled and organized into a Structures Safety Report (NCDOT 2018). Post inspection, the bridge inspectors present the reports to their respective State Bridge Inspection Supervisors, where reviews of the reports are performed prior to approval. State Bridge Inspection Supervisors can return inspection reports to inspection teams for revision and/or improvement prior to final approval. Once approved, the supervisors submit the reports to the SMU staff at NCDOT’s central office in Raleigh.

2.1.4.1 NCDOT Bridge Management System

One important objective of conducting bridge inspections is to monitor the health conditions of the existing structures. The National Bridge Element scores help the FHWA determine the state of a particular bridge (FHWA 2022; AASHTO 2010). Inspection data is often used to facilitate the development of deterioration prediction models (Cavalline et al. 2015; Goyal 2015; Goyal et al. 2016). Software such as the AASHTOWare Bridge Management (BrM) and Bridgit are commercially developed to help state agencies develop and apply state-based probabilistic models to forecast bridge deterioration (Goyal et al. 2016). These bridge deterioration models are based on condition ratings developed with engineering judgment provided by the inspectors, thus making field inspection practices even more important.

2.1.4.2 Conventional Bridge Inspection Process and Challenges

The typical human approach to bridge inspection takes around \$4,500 to \$10,000 (approximately \$5,800 to \$13,000 in 2023) and 1 to 3 days per bridge in the United States (Zulfiqar et al. 2014). With over 13,500 structures in the state of North Carolina, the total amount of money and time spent on bridge inspection is a significant financial burden, coupled with user cost-associated delays. Often, a goal of a public agency is to lower operating costs to save tax dollars, since doing so could please the public and provide operational efficiencies. Azari et al. (2022) conducted research on the impact of implementing UAS into bridge inspection operations. They stated that the Oregon Department of Transportation (ODOT) saved on average \$10,200 while using UAS to assist in bridge inspection operations versus the conventional method. They also pointed out a Minnesota Department of Transportation (MnDOT) research where a particular bridge took the agency 8 days and $59,000 to conduct a conventional inspection, whereas it took only 5 days and $20,000 for the UAS-assisted inspection. Another research included the indirect costs to performing a conventional bridge inspection. Hubbard and Hubbard (2020) explored the potential cost of conventional inspection due to the safety risks surrounding work zone accidents, which is oftentimes an aspect that could be neglected when comparing conventional to UAS-enabled bridge inspections.

Despite a lot of research stating the monetary benefits of performing UAS-enabled bridge inspections, the Idaho Department of Transportation (IDOT) discovered that UASs are not always more cost-efficient. IDOT performed a cost analysis on a fracture critical inspection and concluded that it would have cost $236 more to inspect the structure using a UAS than with traditional hands-on inspection (Azari et al. 2022). This finding demonstrates the importance of bridge candidate selection for UAS-enabled bridge inspection.

Although some small, simple bridges can be inspected within a matter of hours using access equipment that can be carried in a typical vehicle (e.g., ladders), larger bridges may require longer durations and additional access tools such as snooper trucks, boats, and rope access to perform inspections. The inspection time required for some bridges can be days or weeks, incurring significant costs associated with manpower, equipment rental, and traffic control. Significant traffic impacts often occur when inspections require support from snooper truck operations. UASs can significantly help improve inspection efficiency and reduce the time of inspection processes (Cheyne et al. 2019). Reducing the amount of time using a snooper truck may also impact the amount of time required to set up and take down the traffic control for the snooper truck (Banks et al. 2018).

Safety is also a major concern when it comes to bridge inspection (Banks et al. 2018). Multiple research papers acknowledge the improvement of safety of inspection personnel when UAS is used during the inspection process (Azari et al. 2022; Cheyne et al. 2019; Neubauer et al. 2021). According to the Bureau of Labor Statistics, the United States averages more than 120 fatal injuries every year on roadway and bridge worksites (Bridge Masters 2021). When it comes to a typical bridge inspection, the maximum ladder reaches height often approximately 30 feet (Rickus 2022). In other words, methods besides ladders need to be explored when inspecting defects at heights exceeding 30 feet. When addressing an amusement park incident where a 14-year-old fell from a 25 feet park ride, Dr. Robert Glatter of Lenox Hill Hospital in New York City said, “Falls from greater than 30 feet have a high probability of inflicting serious injuries involving the spleen, liver and lungs, along with blunt chest trauma and rib fractures” (Rice 2017). Hence, enabling UASs during bridge inspection practices may help greatly improve field safety (Azari et al. 2022; Cheyne et al. 2019).

However, the deployment of UAS does also present potential safety risks as well. One of the major safety concerns with a cutting-edge piece of equipment such as a UAS is public distraction. A study was conducted where participants were provided with eye-tracking hardware and were instructed to drive in a car simulator. Throughout the driving session, a UAS would be deployed near the roadway for the researchers to observe the typical driver behavior. The research concluded that most drivers were distracted by the UAS, and that multiple drivers glanced at the UAS for more than 7 seconds without looking at the road (Barlow 2019). Therefore, it is not to say that UASs would provide a better inspection environment with no safety risks at all.

The typical bridge inspection process used by the NCDOT is also reviewed in this research. The workflows should include all aspects of a typical UAS-enabled bridge inspection procedure, which should be an expansion of a conventional bridge inspection workflow. Pre-inspection planning processes and post-inspection organizing processes should be considered in order to determine the adjustment of conventional bridge inspection procedures for the inclusion of UAS-enabled bridge inspection procedures.

2.2 Preparation

2.2.1 Preparation

The office preparation of the bridge inspection process includes reading prior the Structure Safety Report, researching access points at the bridge, scheduling personnel, preparing inspection equipment, and other supporting tasks to ensure the inspectors have the tools needed to support the inspection and to help minimize the amount of time the inspectors need to be in the field (NCDOT 2018). Reviewing the bridge's drawings is also a vital pre-inspection activity since a part of the inspection requirement is to obtain the necessary dimensions of the structure (Ryan et al. 2022).

Safety precautions are important when performing bridge inspections according to the Bridge Inspector's Reference Manual (Ryan et al. 2022). Due to random natural occurrences and the random nature of traffic behavior, inspectors should follow Occupational Safety and Health Administration (OSHA) guidelines. Hard hats, vests, steel toe boots, and fully enclosed legwear are just basic requirements upon entering a work site. Depending on the situation, ladders and harnesses can be required as well. At the end of the day, inspectors prepare and use personal protective equipment (PPE) as necessary to keep them safe (Ryan et al. 2022).

When it is determined that there is no suitable access point at a bridge, traffic control may be required since it will help free up some space for the inspectors to access the structure. Traffic control can be very tedious, is inherently dangerous, and often a third-party contractor specializing in this work is retained to perform this job during bridge inspections (Banks et al. 2018). This task includes erecting traffic warning signs, standing up cones, and sometimes flagging for traffic. At the end of the day, the necessity for traffic control depends on the judgment call of the inspectors in charge, with the goal of improving operational safety for the public and for the working crew.

2.2.2 Access

Most bridges span over a body of water, a roadway, or a railroad, a grade change, or combinations of these features. For many of these cases, the terrain might be treacherous and would require further attention to planning the access point(s). The access point should connect two locations, a parking location at the road level and a setup location at the substructure level (Ryan et al. 2022).

Access and parking conditions vary greatly for inspection of individual bridges. Most bridges are not directly adjacent to curb parking and parking lots. The most suitable parking spot for a vehicle may be on the shoulder of the road. In that case, there should be as much clearance between the vehicle and the travel lane (edge line) as possible. Parking should be not only safe from traffic but also flat enough for the ease of loading and unloading equipment (Ryan et al. 2022).

On the substructure level, the setup area should be considerably flat as well. NCDOT bridge inspectors often carry their tablet computers for WIGINS Elements data entry (NCDOT 2018). Some optional companion equipment for tablet computers may be a table, a folding chair, and a wireless keyboard. This setup requires a flat surface as mentioned previously. Of course, in some instances, inspectors might prefer to conduct the inspection first while recording the inspection notes on a notebook, then later transferring the information into WIGINS Elements in the office. The latter method might not even require a setup area. The setup area (substructure level) should have ease of access to any location around and under the bridge for inspection purposes.

2.2.3 Bridge Components and Typical Distress Conditions

The substructure of a bridge is defined by the NCDOT Element Inspection Manual as the columns, pier walls, abutments, piles, pier caps, and footings (NCDOT 2017; Ryan et al. 2022). The substructure is responsible for holding the superstructure and deck above the earth (AASHTO 2010). Substructures are designed to endure earthquakes while still maintaining structural integrity. These components are oftentimes made from steel, concrete, masonry, and timber (Ryan et al. 2022). The most common defects on a superstructure are cracks, patches, and delamination. Delamination is caused by water seeping through the concrete causing corrosion and resulting in the affected area to weaken and lose bond with reinforcing steel. Scour is a phenomenon in which fast-moving water erodes the sediment that sits underneath the bridge foundation. Scour is recognized as the number one reason for bridge collapse (Ayres 2022).

The superstructure of a bridge is defined by the NCDOT Element Inspection Manual as the girders, stringers, trusses, arches, floor beams, and bearings (NCDOT 2017). The superstructure transfers the live and dead loads from the deck to the substructure, and eventually to the foundation (AASHTO 2010; Ryan et al. 2022). According to some inspectors, the most common defects on the superstructure are rusted bearings and spalling on the beams and girders (Rickus 2022). Often, bridge bearings and beams are coated with an extra layer of protective paint or other coating material. However, over time, coatings are susceptible to wear and provide imperfect corrosion protection.

The deck of a bridge is defined by the NCDOT Element Inspection Manual as the decks, slabs, and railings (NCDOT 2017; Ryan et al. 2022). The function of the deck is to hold live traffic and dead loads such as signs. Slabs act as both the deck and superstructure, though it is still considered as a deck component. A common defect found on the deck is asphalt/concrete cracking and issues with railings (such as fasteners loosening) and parapet walls (damage from traffic, cracking) (Rickus 2022). Cracks are often signs of fatigue on the deck due to a large number of traffic cycles but could also be due to other causes (NCDOT 2017; NCDOT 2018; Ryan et al. 2022). The most common types of cracks are transverse cracks across the width of the roadway and alligator cracks at spots of deterioration. Railing fasteners loosen due to vibration caused by passing traffic (NCDOT 2018).

2.3 UAS-Enabled Bridge Inspection

With UASs becoming more prevalent, the civil and construction industry is embracing the trend of flying UASs, or drones (Dorafshan et al. 2021; Duque 2017; Jeong et al. 2020; Neubauer et al. 2021). UASs offer three-dimensional mobility that a human counterpart lacks. This advantage could help improve bridge inspection efficiency (Gillins 2016). A typical human-performed inspection would require ladders or snooper trucks, which are either time-consuming or cost-ineffective (Cheyne et al. 2019). A UAS typically has a built-in real-time camera for not only operation purposes, but also to capture images, which supplements a very important part of the SMU Structure Safety Report (Wells and Lovelace 2017).

Although UASs provide technological advantages that can save time and money, there are still constraints that require the user’s attention. One of the first requirements to operate a UAS is to obtain an FAA certification (Banks et al. 2018; Cheyne et al. 2019). The requirements to obtain a UAS remote pilot certification are to be 16 or older, to be able to read, write, speak, and understand English, to be in good physical and mental condition, to pass the Unmanned Aircraft General- Small (UAG) exam, and to be tested every 24 months after certification on aeronautical knowledge (FAA 2022). The Unmanned Aircraft General- Small (UAG) exam includes the following topics (FAA 2022):

- Applicable regulations relating to small unmanned aircraft system rating privileges, limitations, and flight operation.
- Airspace classification and operating requirements, and flight restrictions affecting small unmanned aircraft operation.
- Aviation weather sources and effects of weather on small unmanned aircraft performance.
- Small unmanned aircraft loading and performance.
- Emergency procedures.
- Crew resource management.
- Radio communication procedures.
- Determining the performance of small unmanned aircraft.
- Physiological effects of drugs and alcohol.

- Aeronautical decision-making and judgment.
- Airport operations.
- Maintenance and preflight inspection procedures.
- Operation at night.

Due to this requirement, either a certified UAS pilot is required to accompany the bridge inspection team, or a bridge inspector would need to be FAA certified (Banks et al. 2018; Cheyne et al. 2019). The latter would be ideal, but more difficult to achieve since obtaining an FAA UAS certification is not a job requirement for becoming a bridge inspector in the state of North Carolina. Therefore, having both a UAS pilot and a bridge inspector gather around a screen during a UAS-enabled inspection is challenging yet necessary in the current environment, since the population of personnel who are both qualified to inspect bridges and certified to fly UASs is small.

2.3.1 Federal Aviation Administration Requirements

The Federal Aviation Administration (FAA) allows state and local government employees to operate UASs under the Title 14 Code of Federal Regulation (CFR) Part 107 (FAA 2022). This regulation restricts the UAS size to under 55 pounds. Additionally, a key component of this regulation is that it prohibits the operations of UAS over traffic and pedestrians for safety reasons. Traffic and pedestrians are two common features associated with many bridges. Because of these limitations, traffic control may be required to perform UAS operations on bridges. This regulation does, however, allow qualified agencies to bypass the process of applying for permission to fly over public space, thereby providing these qualified agencies with more flexibility to utilize UASs (Mallela et al. 2021)

2.3.2 Equipment and Capabilities

UASs are becoming more technologically advanced by the day. From high image definition to obstacle avoidance, different UAS manufacturers offer different capabilities using a range of technologies. A detailed assessment of multiple UAS platforms and a protocol for UAS selection to support bridge inspection activities is provided in Karimoddini et al. (2021).

Safety of the public, the inspectors, and the UAS itself are priorities when conducting UAS-enabled bridge inspections. Some UASs offer safety prevention systems that automatically keep the drone distant from other obstacles (Plotnikov and Collura 2021). A bridge’s most congested area is typically around the bearings. With the piles, bent cap, diaphragm, and beams all located around the bearing, the maneuverable space becomes very congested. Having an automated wall prevention system helps relieve the stress of the new-to-flying inspectors when it comes to the fear of colliding the UAS against the bridge or other objects (Plotnikov and Collura 2021).

Having to fly under lower bridges and even into small culverts requires a drone that is smaller in size. Some commercial UASs are the size of a child and are not ideal due to limited agility. Other UASs have dimensions similar to a thick textbook, which provide improved operational capacities (Mahama et al. 2021, Hewlin et al. 2021, Karimoddini et al. 2021).

Being able to acquire high-quality images via the UASs is vital. The utilization of UASs should yield similar visual resolution to that produced by an inspector since the inspection quality is heavily biased towards visual identifications of distresses. These high-definition pictures would also be optimal for documentation purposes since it is vital that the pictures provide clarity to illustrate the condition of the bridge. A chart compiled by Seo et al. compares different brands and models of available UASs in the market (Seo et al. 2018). Although the researchers indicated the UAS selected to satisfy the requirements of their research, this chart provides a glimpse into the advantages and disadvantages of different UASs, so that others may compare and select the appropriate UASs for their own research needs (Mahama et al. 2021, Hewlin et al. 2021, Karimoddini et al. 2021).

2.3.3 Summary of Other States' efforts

The implementation of UASs is not unexplored in the realm of bridge inspection. Several states, including states such as Oregon and Minnesota, have conducted research on the practicality of utilizing UASs when performing bridge inspections. The FHWA itself sponsored Futron Aviation to study the use of UASs for bridge inspection (FHWA 2021).

A research team from Oregon State University has conducted thorough studies on the application of UAS-enabled bridge inspections for the Oregon Department of Transportation (Neubauer 2021). The team compared the cost of a traditional bridge inspection setup with snooper trucks versus with a UAS. An average $10,000 savings per bridge was calculated when the UAS was utilized. Not only did they conclude that UAS-enabled inspections are more cost-effective than conventional inspections, but UAS-enabled inspection approaches were also identified as safer and more time efficient.

Collins Engineering performed similar research for the Minnesota Department of Transportation (Wells and Lovelace 2017). This study determined that:

1. UASs are more suitable for larger structures based on the subject bridges that the experiments were conducted on.
2. Measurements can be estimated from photos, however information typically obtained from tactile functions cannot necessarily be estimated from photos.
3. UASs that can perform flight without the need of GPS can be of advantage for bridge inspection use.
4. Risks associated with both inspector safety and that of the traveling public can be reduced with the usage of UASs.

Many local transportation agencies are also investigating the use of UASs for bridge inspections under the new FAA title 14 CFR Part 107 regulation (Mallela et al. 2021).

2.3.4 FHWA guidance on UAS-enabled inspection

In October 2019, the FHWA compiled a tech brief on the "Use of small unmanned aerial systems for bridge inspections" (Cheyne et al. 2019). This tech brief is a compilation of UAS-enabled bridge inspection findings similar to the results of the studies from Oregon State University and Collins Engineering as mentioned previously (Gillins et al. 2018). The current FAA regulation focuses on the flight restrictions of UASs.

One major point that the FHWA emphasizes in its publications is that UAS are meant to "assist" human inspectors when it comes to bridge inspections (FHWA 2022; Cheyne et al. 2019). Replacing human inspectors with UASs should not be considered. All bridge inspection work can be performed by a human inspector, but not all work can be done by a UAS (Cheyne et al. 2019).

2.3.5 Previous Workflows for UAS-Enabled Bridge Inspection

Workflows are designed to help guide users in performing certain tasks. The identification of the targeted end user is especially important since each workflow is designed based on those parties. The end user for this work would be the NCDOT and its partnering field inspection personnel. This means that the workflows developed should consider the maturity of performing UAS-enabled bridge inspection, material distress diagnosing and reporting procedures, and overall bridge inspection procedures, within the jurisdiction of the NCDOT. There are currently no workflows published that could guide inspectors on performing UAS-enabled bridge inspections abiding by the NCDOT bridge inspection requirements.

There are workflows that provide broad guidelines to UAS-enabled bridge inspection such as the one shown below in Figure 2.5 created by Chen et al (2019). Another example shown in Figure 2.6 was a workflow created to emphasize the UAS operational aspect during a bridge inspection, such as UAS equipment selection and data processing (Tmušić et al. 2020). Note that this framework is more extensive than the activities required for a routine inspection, where a 3D reconstruction is neither practical nor required.

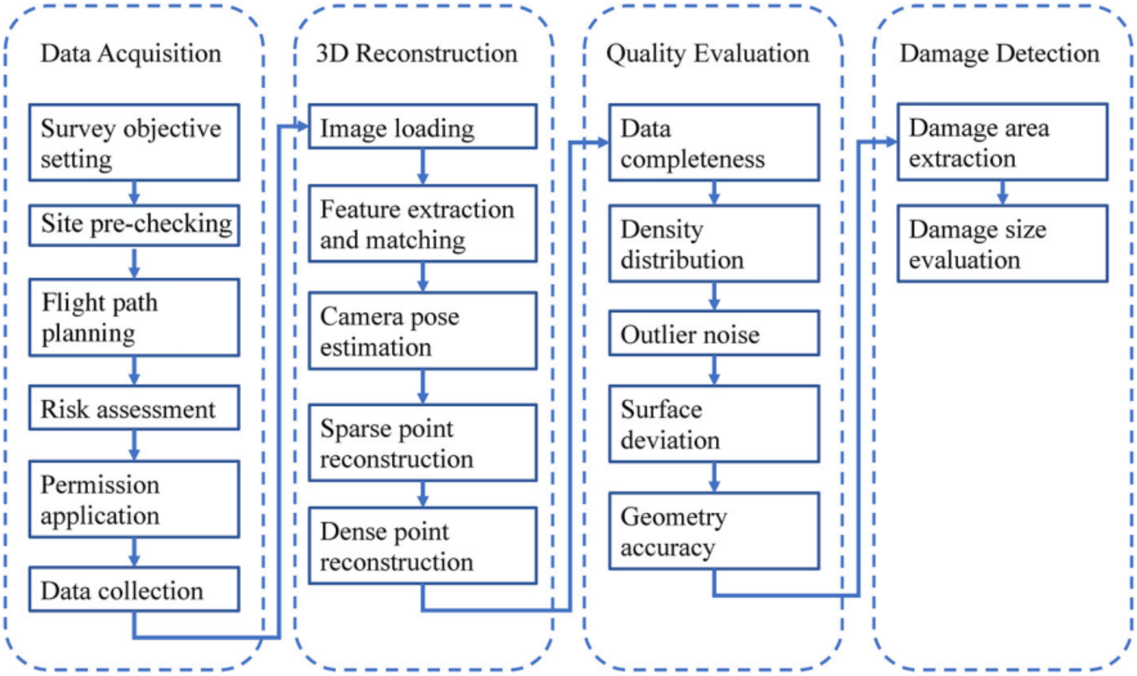


Figure 2.5: Framework for UAV Inspection (Chen et al. 2019).

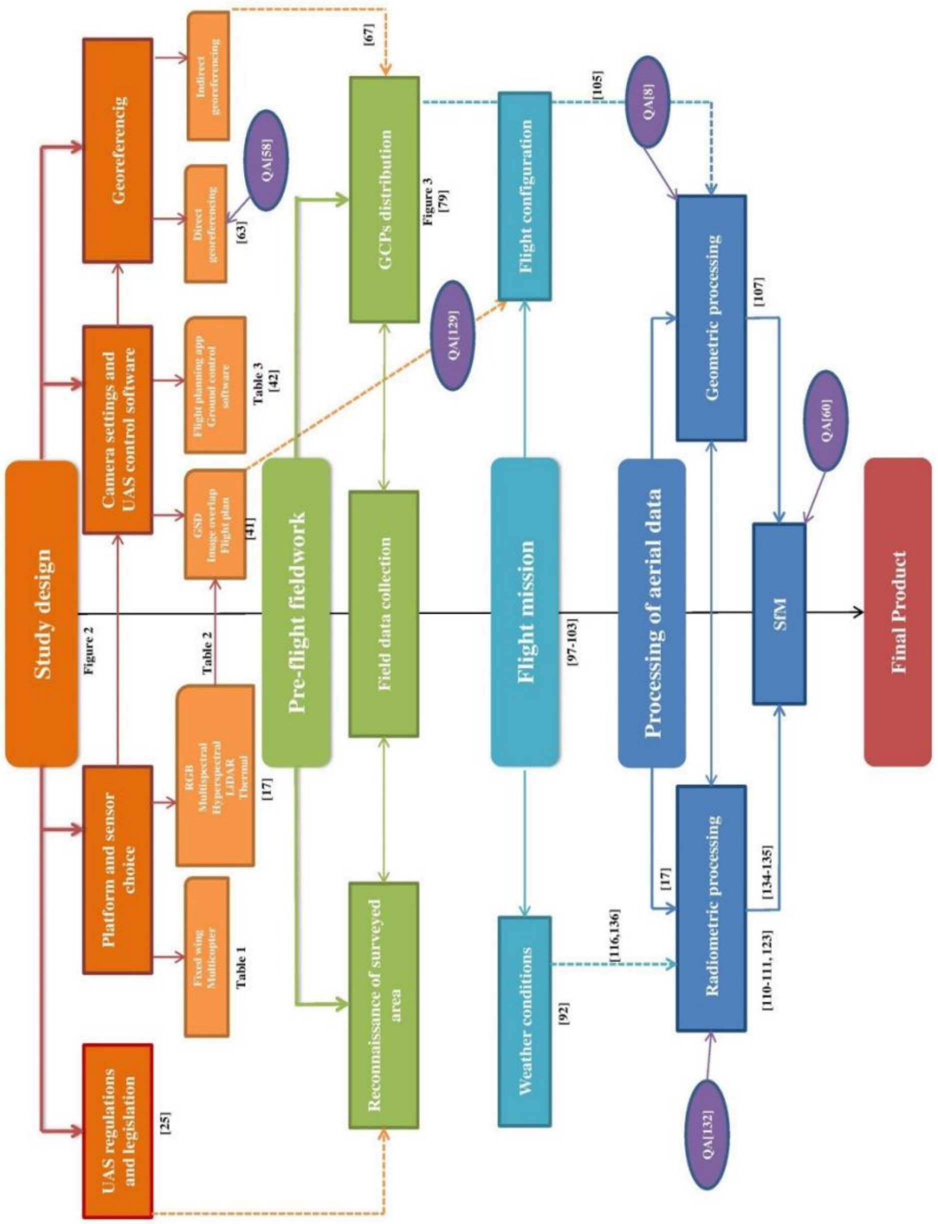


Figure 2.6: Proposed UAS Environmental Mapping Workflow (Tmuši ́c et al. 2020).

Another developed workflow, made by Gillins (2016), includes operational components such as UAS selection, flight planning, safety plan, data collection, and data processing (Figure 2.7). This workflow also provides guidance on the overall UAS-enabled bridge inspection process but does not include detailed procedures for element inspections. The framework is also fairly high-level and does not provide specifics associated with progressing from one end of a structure to another in a rational manner, or information to support data collection for specific materials, elements, or distresses.

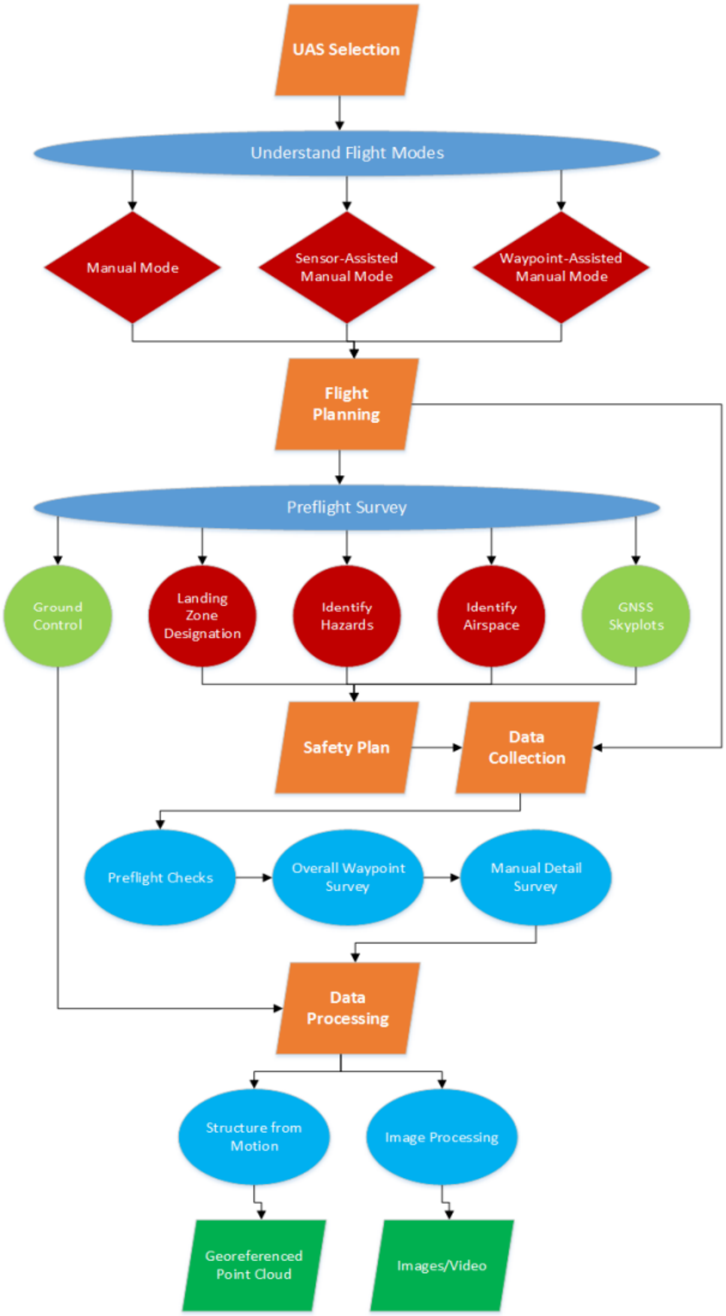


Figure 2.7: UAS Based Bridge Inspection Workflow (Gillins 2016).

Another UAS workflow developed by Wells and Lovelace in 2017 is shown in Figure 2.8 (Wells and Lovelace 2017). This workflow represents a higher level of guidance on how a UAS would be integrated into a bridge inspection operation. This workflow emphasizes the capturing of data and the post-inspection process.

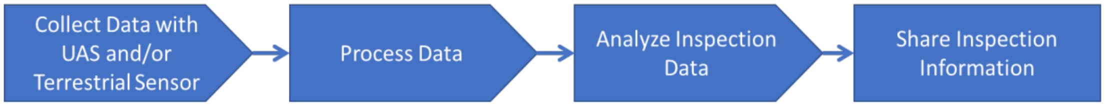


Figure 2.8: General UAS Workflow (Wells and Lovelace 2017).

Most current workflows focus on providing a framework for the overall inspection process, such as the selection of the UAS and the process in which data is collected, and do not contain the level of detail that would provide useful guidance to inspectors arriving on-site. There is yet to be a workflow developed that incorporates inspection type, bridge components (NBE and BME), and material type.

2.3.6 Opportunities for Workflow Improvement

To accompany UAS-enabled bridge inspection, workflows have been created to assist bridge inspectors (Chen et al. 2019; Gillins 2016; Tmuši´c et al. 2020). The FHWA had included workflows in Chapter 5 of the *Report Collection of Data with UAV for Bridge Inspection* (Gillins et al. 2018). However, these workflows serve as a higher-level guidance towards UAS-enabled bridge inspection. From observing the bridge with the UAS to processing distress data, these workflows provided only the big picture overview of how UAS would be involved in the bridge inspection process. The purpose of those existing workflows is to provide preliminary instructions on how UASs would be integrated into the field.

Workflows published based on previous research do not contain the granularity and level of detail required to fully support inspectors interested in using a UAS to enhance an inspection. Workflows with step-by-step guidance on how to incorporate UASs into a bridge inspection operation could provide a useful tool to support more broad use of UAS by inspection teams.

A workflow that is designed to incorporate NCDOT bridge inspection requirements and preferences along with FHWA bridge inspection standards is yet to be developed and published. A workflow that includes specific bridge inspection action items such as how a particular distress (such as a crack in concrete) should be treated and what departmental action items should be triggered could assist NCDOT bridge inspection teams when conducting UAS-enabled bridge inspections. Guidance to help bridge inspectors identify whether a particular bridge or inspection type is compatible with UAS-enabled inspection techniques has also not yet been developed and published.

2.4 Research Needs

To integrate UAS-enabled bridge inspections into current NCDOT practices, all aspects of a bridge inspection operation should be considered. This includes the habits and preferences of different inspection teams. Workflows were developed to guide NCDOT and PEF inspectors on how to incorporate UASs into current bridge inspection operations.

It is also important to recognize that not all bridges may benefit from the usage of UAS when performing bridge inspections. Furthermore, not all bridges may be eligible for UAS-enabled bridge inspections due to FAA restrictions. Therefore, the analysis to identify all bridge characteristics that could potentially impact the suitability of a bridge for the usage of UAS was performed.

2.4.1 Workflows to Support UAS-Enabled Inspection of Bridges of Different Types

Since the usage of UAS in bridge inspection is still uncommon, the NCDOT saw the need for workflows to help guide inspectors along the process of utilizing UASs to perform bridge inspection operations. Workflows that incorporate NCDOT bridge inspection procedures, with inspector habits considered, may help the integration of UASs into current NCDOT bridge inspection practices. The level of UAS integration should also be considered to help improve the efficiency of conventional inspection operations.

2.5 Methodology to Identify Candidate Bridges for UAS-Enabled Inspection

To understand which bridge characteristics defined within the NBI could impact the usage of UAS during a particular bridge inspection, a committee of UAS-enabled bridge inspection and conventional bridge inspection experts were surveyed via the Delphi method. The surveyed results helped the development of an algorithm that would scale the NBI characteristics according to the importance of their impact towards the suitability of performing a UAS-enabled bridge inspection.

3 WORKFLOWS TO SUPPORT UAS-ENABLED INSPECTION OF BRIDGES OF DIFFERENT TYPES

3.1 Methodology

To assist in the integration of UAS operations into current NCDOT bridge inspection procedures, a series of workflows have been developed. The workflows are intended to serve as guidance for bridge inspectors and engineers that intend to utilize UASs during bridge inspection operations. The workflows will not serve as UAS piloting manuals, however, they will instead be integrated into bridge inspection standard operating procedures derived from NCDOT bridge inspection requirements, as well as field practices, and used as companion tools when inspection teams conduct UAS-enabled bridge inspection.

Currently published workflows that support UAS-enabled bridge inspection are typically limited to high-level action items such as "data collection" and associated recording and processing procedures, rather than focusing on specific bridge inspection action items targeting the procedure for inspection of individual distresses (Gillins 2016). To better serve the NCDOT, more detailed workflows, including specific action items that would guide inspectors on how to diagnose distresses and document different data were incorporated into the developed workflows. To encompass the significant number of action items potentially encountered in different phases of a bridge inspection operation, the workflows were organized using a "level system." This system breaks down an overall bridge inspection operation into three levels, each incorporating its own action items to best optimize the amount of information within any workflow.

The general steps guiding the development of the UAS-enabled bridge inspection workflows were to first develop workflows documenting and reflecting typical inspection practices performed without the use of UAS. After these workflows were developed, they were modified to support the integration of UASs. In summary, the UAS-enabled bridge inspection workflows were developed through the following tasks:

1) Review FHWA bridge inspection requirements.
2) Review NCDOT bridge inspection requirements.
3) Understand NCDOT bridge inspection procedures. Table 3.1 provides a list of field visits that were taken to better understand NCDOT bridge inspection procedures, as well as operational preferences of different inspection teams.
4) Review WIGINS Elements software framework, functionality, and data entry processes.
5) Understand NCDOT and PEF inspector preferences in performing inspections, considering different bridge characteristics, site characteristics, traffic conditions, and access needs.
6) Integrate inspection photography and data recording needs into the workflows.
7) Develop typical workflows for conventional bridge inspections performed without UAS involvement.

Develop preliminary UAS-enabled bridge inspection workflows by integrating the UAS into the conventional bridge inspection workflows.

3.1.1 NCDOT Inspection Practices

The NCDOT and its partner PEFs follow the NCDOT Manual for Bridge Element Inspection when conducting bridge inspections, as well as the SMU Inspection Manual. Although the SMU Inspection Manual provides clear guidance on how a bridge inspector should approach bridge inspections, there is flexibility in implementation to accommodate each inspector's preferences. The SMU Inspection Manual focuses on the expectations for the end results while having minimum input on some of the procedural requirements. Therefore, inspection approaches and techniques vary amongst different groups of inspection teams.

Since there is not a "one size fits all" inspection procedure, the workflows were developed in a generic way that could be used by any inspection personnel. To understand the inspection procedure and approaches used by different bridge inspection teams, nineteen different bridge inspections conducted by

NCDOT and PEF inspection teams were observed. Timber structures were not observed due to the relative sparsity of these structures, so the SMU Inspection Manual was heavily relied upon when developing the workflow for bridges of this material type. The inspection of an aluminum culvert was also observed, though due to the lack of presence of aluminum structures as a whole, aluminum inspection workflows were not developed. Eleven of these structures were concrete structures, seven were steel structures, and one was an aluminum culvert. NCDOT suggested prioritizing the observation of concrete structures due to their relative prevalence in the NCDOT inventory.

Different materials have different inspection requirements and acceptance criteria per the inspection manuals. For example, the permitted size of a crack in concrete is very different than in steel. However, most inspection "procedures" are identical, from a broader perspective, regardless of the material. Although the different materials have different distress types and inspection criteria, the approach to how all materials are inspected is largely similar from a practical standpoint.

A bridge inspection operation is comprehensive, with a lot of site-specific and structure-specific nuances and scenario-specific conditions that are not mentioned in the inspection manuals. Most languages in the SMU Inspection Manual and the NBIS refer to the analyses, classification, and recording of distresses. In order to develop workflows supporting the integration of UAS into bridge inspection operations, all facets of an inspection operation should be considered. The purpose of observing bridge inspection operations conducted by the NCDOT and PEF inspection teams was to understand the extent to which action items pertaining to an inspection operation should be incorporated into the workflows. Table 3.1 is a list of visits conducted, beginning March 2022, through September 2023.

Table 3.1: List of Structures Visited During NCDOT Routine Inspections.

VISITED DATE	STRUCTURE NUMBER	COUNTY	GIRDER MATERIAL	FEATURE INTERSECTED
3/22/22	890362	Union	Concrete	Water
3/22/22	890552	Union	Concrete	Highway
6/13/22	590083	Mecklenburg	Concrete	Water
6/13/22	590919	Mecklenburg	Concrete	2 lane road
6/28/22	890490	Union	Concrete	Highway
6/28/22	890549	Union	Concrete	Highway
8/17/22	590231	Mecklenburg	Steel	2 lane road
8/17/22	590524	Mecklenburg	Aluminum	Water
9/21/22	890178	Union	Concrete	Water
2/10/23	170023	Catawba	Steel	Water
2/11//23	170091	Catawba	Steel	Water
2/18/23	170005	Catawba	Steel	Water
2/19/23	170003	Catawba	Steel	Water
2/21/23	640012	New Hanover	Concrete	Water
3/16/23 & 3/17/23	270072	Dare	Concrete	Water
8/23/23	000042	Alamance	Steel	Water
8/23/23	000086	Alamance	Concrete	Water
8/23/23	000210	Alamance	Concrete	Water
9/27/23	860032	Swain	Steel	Water

The inspections performed during the site visits listed in the table were all routine inspections. The development of the workflows is centered around routine inspections, although the applicability of the workflows for other inspection types could also be considered. Major action items are similar for all bridge inspection types, especially during the pre-inspection and post-inspection phases.

A typical inspection trip could be split into three stages: pre-inspection, during inspection, and post-inspection. It was observed that the action items pertaining to a bridge inspection operation could be best split into these three stages. It was observed that the majority of the inspection time was associated with activities performed in the during-inspection process, followed by the post-inspection process.

3.1.1.1 Pre-Inspection Process

The pre-inspection process includes action items such as reviewing the structure condition, planning the inspection approach and/or pattern, preparing for the weather conditions, and other considerations associated with the location such as access, traffic, water, land, and utility features. The purpose of this stage of an inspection operation is to understand the condition of the bridge during the anticipated date of inspection, the conditions at the site that might influence the inspection, and plan for the inspection operation accordingly. While many teams conducted different action items during the pre-inspection stage, many common action items were observed. These action items were completed either in the office before the inspection date, or on-site before performing inspections. The following is a list of common actions performed during the pre-inspection phase:

1) Reviewing the previous bridge inspection report of the structure.
2) Determining the required number of inspection personnel.
3) Determining the required inspection access equipment.
4) Determining the inspection pattern and route.
5) Planning traffic control measures.
6) Assignment of inspection tasks by team leader.
7) Setting up inspection equipment.
8) Ensuring traffic control setup.

Reviewing the previous bridge inspection report of the structure entails both reviewing and understanding of the previous inspection report conducted for the structure as well as the previous Structure Safety Report. Doing so allows inspection personnel to understand the pre-existing distresses reported in the previous inspection cycle, as well as the reported severity of the distresses. Distresses that were previously deemed as Priority Maintenance requests or Priority Action Requests would be inspected more closely when the team conducts the inspection. Other information on the Structure Safety Report that may be reviewed includes the bridge geometry and traffic conditions. Reviewing this information enables the inspection team to anticipate the traffic control measures, identify access approaches, and forecast the time necessary to complete the inspection operation.

The second action item determining the required number of inspection personnel is based on the bridge geometry (size, vertical clearance, traffic condition) as well as the inspection type. Most inspection operations observed consisted of 2 inspectors: a bridge inspection team lead, and an assisting inspector. When the bridge requires a snooper truck and traffic control, there may be more personnel to assist with the inspection operation, with the additional personnel serving functions such as traffic control, operating the snooper truck and/or bucket, and serving as personnel in a safety boat (for bridges over waterways). The amount of personnel necessary to complete a bridge inspection operation is determined in advance by the bridge inspection team lead.

The determination of required access equipment is following the inspection team’s review of the structure. Similar to the previous action item, this action item depends on the bridge geometry and the inspection operation type. Standard access equipment observed during the inspection trips consisted of ladders. Access equipment that was deemed as required for special situations were bridge inspection platforms, snooper trucks, and bucket trucks. Structures that are larger or more difficult to access are generally tasked to PEFs, instead of being inspected by NCDOT personnel. These are typically the structures that may require extra access equipment.

The next action item is the determination of inspection pattern and path/process. This refers to the order in which the individual bridge components will be inspected. The NCDOT inspection report follows a south-to-north reporting procedure, such that the reports are ordered beginning from the southernmost element of a structure and ending at the northernmost element. Although there is no rigorous requirement on the pattern by which an inspection team should abide, most inspection teams follow the typical south-to-north pattern to align with the reporting process.

It was also observed that for most structures, the deck would be treated differently than the superstructure and substructure. None of the decks observed required access equipment since they were all accessible from a level roadway. On the other hand, especially with complex structures, the superstructures and substructures could be difficult to access due to the vertical clearance of those components and the fact that oftentimes the substructures sit in water. Because of the difficulty in coordinating schedules with third-party inspections on intended dates, the inspection teams prioritized the pattern of the inspection operations to match the availability of the access equipment and conducted the deck inspection before or after the required operations.

After the inspection team lead determined the amount of personnel and equipment required, the logistics of the operation would be determined. The weather conditions would also be considered when planning for logistics. Bridge inspections are typically conducted in dry conditions; however, it is up to the bridge inspection team lead to determine the suitability of the weather conditions for the operations. The need for traffic control would also be considered as well. Generally, team leads would be familiar with the NCDOT requirements for traffic control. Traffic control typically occurred during the more complex bridge inspections that involved extra access equipment. The end goal of traffic control is to ensure the safety of the inspection team, as well as the public.

The previous action items mentioned above mostly occur before the day of the bridge inspection operations. The remaining action items are pre-inspection action items that are to be completed on-site, pending the situation of the personnel, traffic conditions, and real-time environmental constraints. Upon arrival at the structure, the bridge inspection team lead would assign inspection tasks to the inspection team members.

Prior to setting up the inspection equipment, the inspection team would select a suitable location to park their vehicles. Once a safe and accessible location had been selected and the vehicles were parked properly, the inspection team would begin setting up inspection equipment. Typical inspection equipment needed during an operation included a tablet or PC with WIGINS Elements software installed, pencils, notepads, the previous Structure Safety Report (digital or paper), measuring tape, vests, hard hat, ladder, camera, chalk, and flashlight. The tablet and PC are used to record distresses and dimensions into WIGINS Elements. Some inspection teams chose to do this after the bridge inspection operation in an indoor location. This choice is based on the preference of the inspection teams, where most inspection teams preferred writing inspection notes on notepads and then later transferring the notes into WIGINS Elements. Inspectors found it easier to maneuver around the structures with a notepad than with a laptop. With the need to walk in difficult landscapes, inspectors found laptops difficult to carry and protect.

3.1.1.2 Inspection Process

The general procedure of a bridge inspection can be viewed to be similar across each type of bridge inspection (routine, initial, damage, etc.). There are certain safety measures and inspection action items that are required for all bridge inspections. Although other inspection types were researched, the routine inspection was the only type of inspection operation that was observed during the participating bridge inspections. This stage of the inspection process focuses on the day of the inspection operation, where the recording and diagnostics of distresses are performed.

Chalk or lumber crayon was used during the inspections to indicate locations of distresses on the structure. This helped the inspectors keep track of completed distress inspections and also helped reviewers of the inspection report to determine the size of the distresses through the photos. Sometimes the marks from previous inspection cycles would be still visible, which helped the current inspection team identify pre-existing distresses more easily. A handheld camera was typically used to capture photographs of distresses, as well as images of different perspectives of the bridge. The photographs are required to be inserted into the inspection reports and are considered a vital part of the inspection process.

The NCDOT Manual for Bridge Element Inspection (NCDOT 2018) provides a detailed description of how each distress is classified based on the material and element that it is located on. In addition, the manual provides a 1 through 4 condition rating (1-good, 2-fair, 3-poor, and 4-severe) based on the extent of the observed condition on an element. The unit of quantities of each element is also given in this document. Although the NCDOT Manual for Bridge Element Inspection is detailed, there are simply too many inspection criteria for different material types of different elements for all to be encompassed into a single workflow. Alternatively, the SMU Inspection Manual (NCDOT 2018) provides a shorter list of distress conditions that would be classified as either a Critical Finding, Priority Maintenance, or Routine Maintenance action. This way the most severe distresses (Critical Findings) are given greater emphasis, and it allows for the inspection team to determine the severity of the distresses more swiftly. These two manuals serve as the main reference during a typical bridge inspection operation.

3.1.1.3 Post Inspection Process

After all required measurements have been obtained, and all distresses have been inspected, recorded, and photographed, the inspectors compare notes to make sure that the data collected are correct and adequate. If there is missing data, the inspectors immediately re-observe or re-measure the component, distress, or other feature while on site. The photographs taken are also verified to ensure that the necessary photographs to compile the inspection report are consistent, and that all photographs are of presentable quality.

Once all inspection data have been validated, the inspectors then input all data into the WIGINS Elements software. This software helps inspectors record all inspection data and measurements, as well as the related streambed profiles and photographs pertaining to the condition of the structure. The software identifies the Priority Maintenance and Critical Finding distresses reported by the inspectors and notifies the Structures Management Unit (SMU) of any of these conditions upon the submission of the report. This is known as the Priority Action Request or PAR. The PAR-notified distresses are then further evaluated by the SMU, which reclassifies the distress as either a Routine Maintenance item, Priority Maintenance item, or Critical Finding. The necessary actions to provide remedy to the distresses are determined through the reclassification process.

3.1.2 Development of Workflows for UAS-enabled bridge inspection

Workflows were developed to guide users through the integration of UASs into current inspection operations. This work focused on the bridge inspection aspect when developing the UAS-enabled bridge inspection workflows. There are many action items required to be considered in the UAS aspect, though this work assumes that the pilot is knowledgeable and cognizant of the planning, maintenance, and operation of the UASs. Specific UAS action items were mentioned only when it pertains to a bridge inspection operation. The procedural integration of UAS into bridge inspections to maximize bridge inspection efficiency using the right tools and approaches is the focus of these workflows.

The purpose of the UAS is to maximize the efficiency of inspection time and cost while reducing safety risks for the inspectors. The UAS should serve as a tool only to assist inspectors because bridge inspection is ultimately a task that heavily relies on human senses and previous experience. Although sensing technologies are advancing, at the time of this study, the role of the UAS was identified as being limited to providing visual assistance to the inspectors. A routine inspection requires fewer hands-on activities, therefore a UAS was deemed beneficial for performing this type of inspection operation.

Whenever hands-on activities are required, it is usually for sounding concrete patches, removing rust from steel, removing dust from concrete spalls, or removing debris to inspect an element. However, it was observed that during a routine inspection, these tasks were not conducted frequently relative to the entirety of the bridge inspection operation. A lot of distresses observed could be identified and classified visually. A UAS could serve as a remote camera that could be controlled at the will of the inspection team. Not only would inspectors be able to view the distress from afar via the UAS, but photographs and videos could also be captured as a part of the inspection reporting process.

To map a more clear path for the integration of the UAS into bridge inspection procedures, different sets of conventional bridge inspection workflows were developed and then modified to integrate the UAS. Most of the developed workflows have two versions, a conventional workflow and a UAS-enabled workflow. This allows users to compare both methods of bridge inspection and to help new users learn the UAS-enabled bridge inspection workflows alongside the conventional workflows.

The complete process of a bridge inspection operation with the integration of UAS could be split up into the three major stages as described previously: pre-inspection, during inspection, and post-inspection. The tasks included in the "during inspection" stage alone are very comprehensive and could have multiple decision trees pertaining to this stage of the inspection. Because of this, the workflows were separated into different levels to fully capture all aspects of UAS-enabled bridge inspection operations.

The following is a list of workflows that were deemed necessary to capture the full spectrum of a UAS-enabled bridge inspection operation:

- Overall Inspection Framework Workflows: Workflows that describe the three major stages associated with conventional and UAS-enabled bridge inspection operations.
- General Bridge Inspection Workflows: Workflows that describe the "during inspection" stage action items, more specifically the inspection procedure in relation to how and when the UAS should be integrated throughout the inspection process.
- Material Element Inspection Workflows: Workflows that describe how an inspection team should approach inspecting a type of distress on a certain type of material conventionally and with UAS.
- UAS Required Structures Photos Workflow: A workflow that describes how an inspection team could use a UAS for photographs of a structure required upon each inspection operation.

After observing the typical bridge inspection procedures, it was determined that UASs could assist inspectors in most aspects of bridge inspections. Even inspection types beyond routine inspections could take advantage of UAS capabilities. This is due to the fact that all inspection operations require photographs of certain angles of the structures, as defined by the SMU Inspection Manual. These photographs could be obtained via UAS in a swift manner, with better vantage points (and improved safety) than an inspector with a handheld camera on foot.

It was also learned that UASs could help inspectors quickly identify locations of distresses that may require hands-on inspection. To reduce time, UASs would identify these locations during the preliminary scan of the structure, then the inspectors could coordinate for access equipment to be used on locations where hands-on would be required. If snooper trucks are required, the UASs could help inspectors identify these locations on the structure, and perform targeted hands-on inspections, rather than scanning the entire structure via a snooper, which would take a much longer time.

3.2 Workflows

Workflows were produced from both a conventional standpoint, along with versions that integrate UAS operations. The term "UAS-enabled" describes workflows that integrate UAS into their procedures. The result of the development is a three-level workflow system that captures the full bridge inspection process, reflects NCDOT and PEF approaches and complies with SMU inspection requirements.

The conventional and UAS-enabled versions of the Overall Inspection Framework Workflow were the only level 1 workflows developed. These workflows capture a general process that would typically be followed during a bridge inspection operation. These workflows provide more in-depth action items that occur during the planning stage of a bridge inspection, as well as during the post-inspection stage of a bridge inspection. Action items during the inspection stage are described in greater detail in the lower-level workflows.

The level 2 workflows, also known as the conventional and UAS-enabled General Bridge Inspection Workflows, capture the inspection stage procedures. The conventional version of this workflow includes reachable stage and accessing equipment stage procedures. The reachable stage includes the inspection of items that the inspection team could reach on ground, whereas the access equipment stage entails the inspection of items where access equipment is required. The UAS-enabled version of the workflow leaves the use of the access equipment as the last inspection task if inspectors require closer inspection of the items or need to perform hands-on inspection tasks.

At level 3, the conventional and UAS-enabled Material Element Inspection Workflows capture material specific inspection procedures and decision trees. These workflows help inspection personnel identify "Critical Findings" as defined by the SMU Inspection Manual based on the material. Further action items that would be required to record material distresses can also be found in these workflows.

In addition to the Element Inspection Workflows, another level 3 workflow that was developed was the UAS Required Structure Photos Workflow. As previously mentioned, not all structures are suitable for UAS-enabled bridge inspection, meaning that the UASs may not be able to efficiently perform inspections due to the inspection material or operation type. However, most bridge inspections require photographs of certain angles of a bridge, and this is where the UASs could help in those specific operations.

Most workflows were developed through multiple iterations, with edits and modifications made based on information obtained during the series of inspection site visits, as well as feedback from NCDOT and PEF inspectors. Changes were made over the course of the project to more accurately describe the action items in each workflow. The changes may be as simple as clarifying the verbiage to more significant modifications affecting the order of tasks and actions. Major changes amongst each iteration of each workflow will be described in the following sections. Iterations of the workflows, along with detailed explanations of the enhancements and changes are presented in Wu (2023). **For clarity, only the final versions of workflows are presented here in the body of this report. Previous iterations are included in Wu (2023) with a discussion on the evolution of the workflow from its initial to final forms.**

3.2.1 Level 1 Overall Bridge Inspection Framework Workflows- Conventional and UAS-Enabled

The Overall Bridge Inspection Framework Workflow was developed to map out the overall process of a bridge inspection operation. This workflow captures the major action items conducted by an inspection team during the planning phase, inspection phase, and post-inspection phase of a bridge inspection operation. These are the action items that were observed and described in the previous section.

Several iterations were required to develop the Level 1 workflow and are described in Wu (2023). Upon approaching the workflow, the user is directed to one of the three major branches: Pre-Inspection Process, Inspection Process, and Post-Inspection Process (Figure 3.1). The pre-inspection and post-inspection branches can be further broken down into "In Office" and "In Situ" operations. As the names suggest, some tasks should be performed in the office prior to the day of inspection, or on site right before the inspection begins. Similarly, some actions should be performed on site as soon as the inspection process is completed, and some actions should be performed in the office after all fieldwork has been verified and completed. This workflow has a more detailed breakdown of the action items conducted before and after the inspection process. This workflow is the only one that includes action items pertaining to the planning process and organization process of a bridge inspection operation, whereas the inspection process branch is to be expanded into the level 2 and level 3 workflows.

The three colors used in this workflow pertain to each phase of the bridge inspection operation, allowing users to easily identify which action items are included in a particular phase. The pre-inspection process allows users to familiarize themselves with the structure that is under inspection and prepares for the bridge inspection operation accordingly. This branch also allows users to plan for the flight path of the UAS, and understand any limitations imposed by the bridge on site conditions that may inhibit UAS operations. When arriving on site, the workflow guides users to select a base station to serve as a take-off and landing spot for the UAS, as well as set up vantage points to allow the inspector and the pilot to communicate effectively.

To guide inspectors and/or pilots, commentary boxes were added to explain some action items. The commentary boxes are labeled with numbers, corresponding to different cells. A similar labeling system was used for all workflows with commentary boxes. In this iteration, a total of 5 commentary boxes were provided on the right side of the workflow, as shown in Figure 3.2.

In the pre-inspection branch, the action item “Traffic control planning” was added to direct users to anticipate any necessary traffic control measures that may need to be provided during the day of the inspection. Traffic control measures may change the bridge inspection pattern, especially with respect to prioritizing the inspection of the components of the bridge that may require traffic control, so that traffic control can be limited to as short a duration as required. A loop with the question “Are there more spans to inspect?” is included to represent the iterative process required to inspect span by span. It was also observed that inspectors typically started their inspections from one side of the substructure, worked their way up towards the superstructure, and then moved on to the other substructure of the same span. The “Yes” and “No” prompt, provides users the ability to return to a previous cell to conduct the inspection of another loop. if necessary.

The final versions of the workflow include both a conventional version (Figure 3.1 and 3.2) and a UAS-enabled version (Figure 3.3 and 3.4). For the UAS-enabled workflow, the post-inspection branch includes action items related to the organization of measurements and photographs. Actions associated with review, recapture, and archiving are included for both UAS and handheld camera photos. The “Photo relabeling” cell directs users to relabel photos taken by UASs, since they may be labeled differently than handheld cameras. The other cell “UAS photo storage in drive” directs users to store the UAS photos on hard drives. After the UAS completes bridge inspection tasks, transfer of the data from the UAS to a hard drive is required to allow users to compile inspection reports later via a laptop.

The UAS-Enabled Overall Inspection Framework Workflow resembles the conventional version in that the overall scope and procedures are the same, with the exception of embedded UAS operations. The UAS action items were inserted into the overall procedure considering observations of field trials conducted by other parties. Similar to the conventional version of the workflow, the UAS action items described in this workflow are mainly focused on the pre-inspection and post-inspection branches with an identical inspection process branch. The commentary cells associated with this workflow address the number of inspection personnel required, traffic control planning, bridge inspection pattern, photo relabeling, and UAS photo storage in drive. These commentary boxes were made to address action items pertaining to UAS operations. Figure 3.5 depicts the differences between the conventional and UAS-enabled workflows.

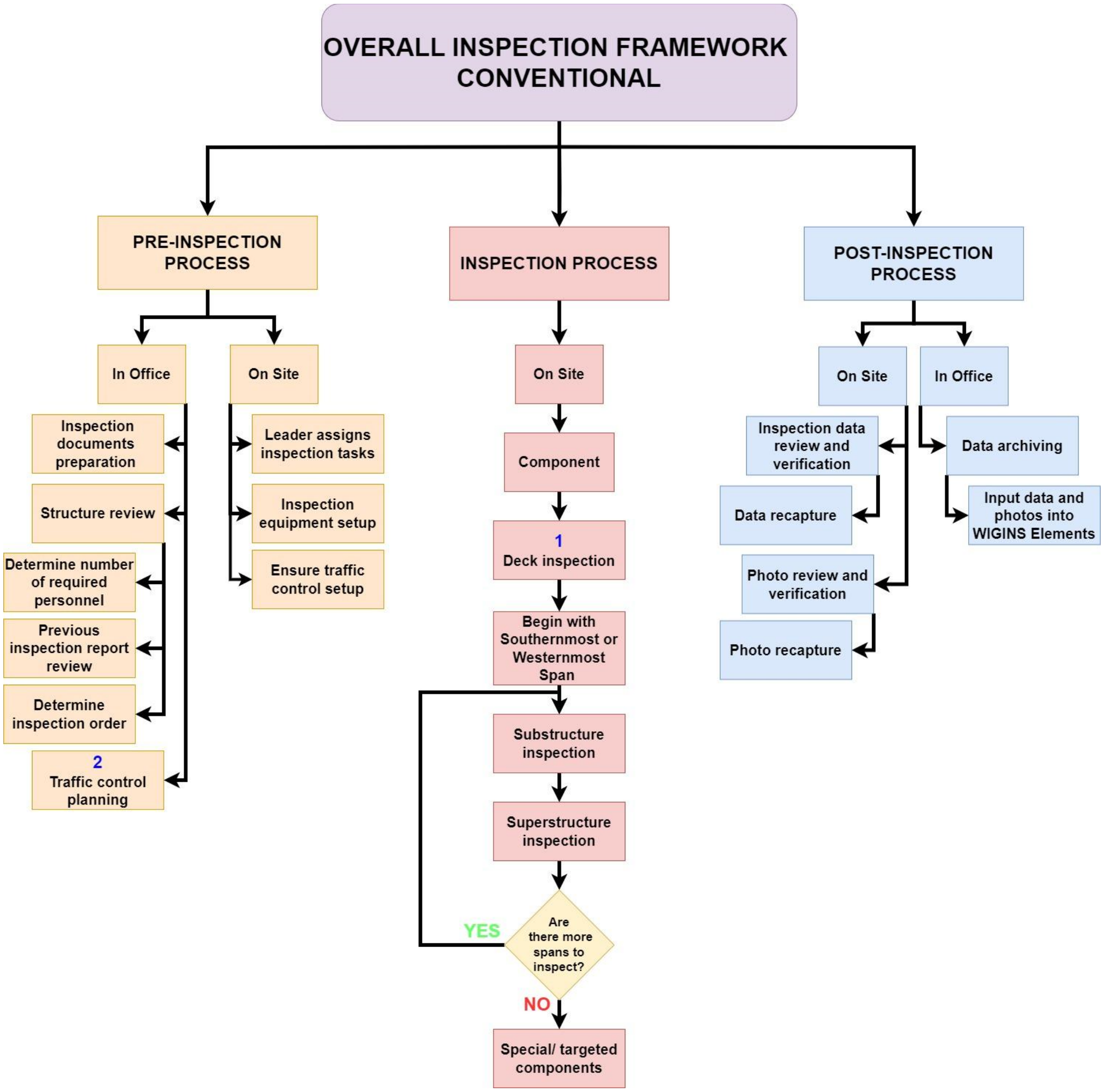
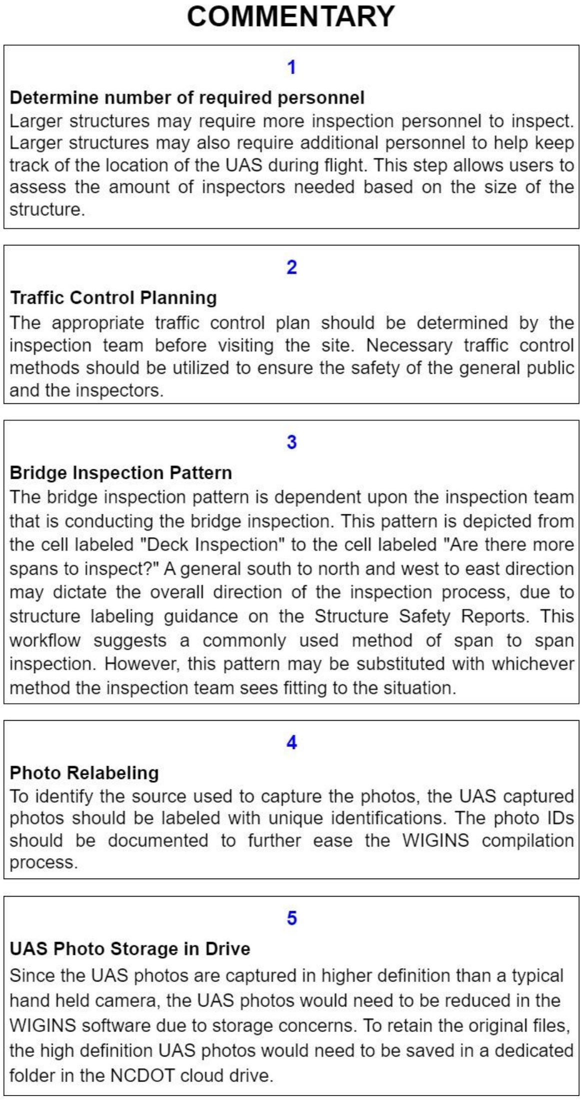


Figure 3.1: Conventional Overall Inspection Framework Workflow.



COMMENTARY

1

Determine number of required personnel

Larger structures may require more inspection personnel to inspect. Larger structures may also require additional personnel to help keep track of the location of the UAS during flight. This step allows users to assess the amount of inspectors needed based on the size of the structure.

2

Traffic Control Planning

The appropriate traffic control plan should be determined by the inspection team before visiting the site. Necessary traffic control methods should be utilized to ensure the safety of the general public and the inspectors.

3

Bridge Inspection Pattern

The bridge inspection pattern is dependent upon the inspection team that is conducting the bridge inspection. This pattern is depicted from the cell labeled "Deck Inspection" to the cell labeled "Are there more spans to inspect?" A general south to north and west to east direction may dictate the overall direction of the inspection process, due to structure labeling guidance on the Structure Safety Reports. This workflow suggests a commonly used method of span to span inspection. However, this pattern may be substituted with whichever method the inspection team sees fitting to the situation.

4

Photo Relabeling

To identify the source used to capture the photos, the UAS captured photos should be labeled with unique identifications. The photo IDs should be documented to further ease the WIGINS compilation process.

5

UAS Photo Storage in Drive

Since the UAS photos are captured in higher definition than a typical hand held camera, the UAS photos would need to be reduced in the WIGINS software due to storage concerns. To retain the original files, the high definition UAS photos would need to be saved in a dedicated folder in the NCDOT cloud drive.

Figure 3.2: Conventional Overall Inspection Framework Workflow.

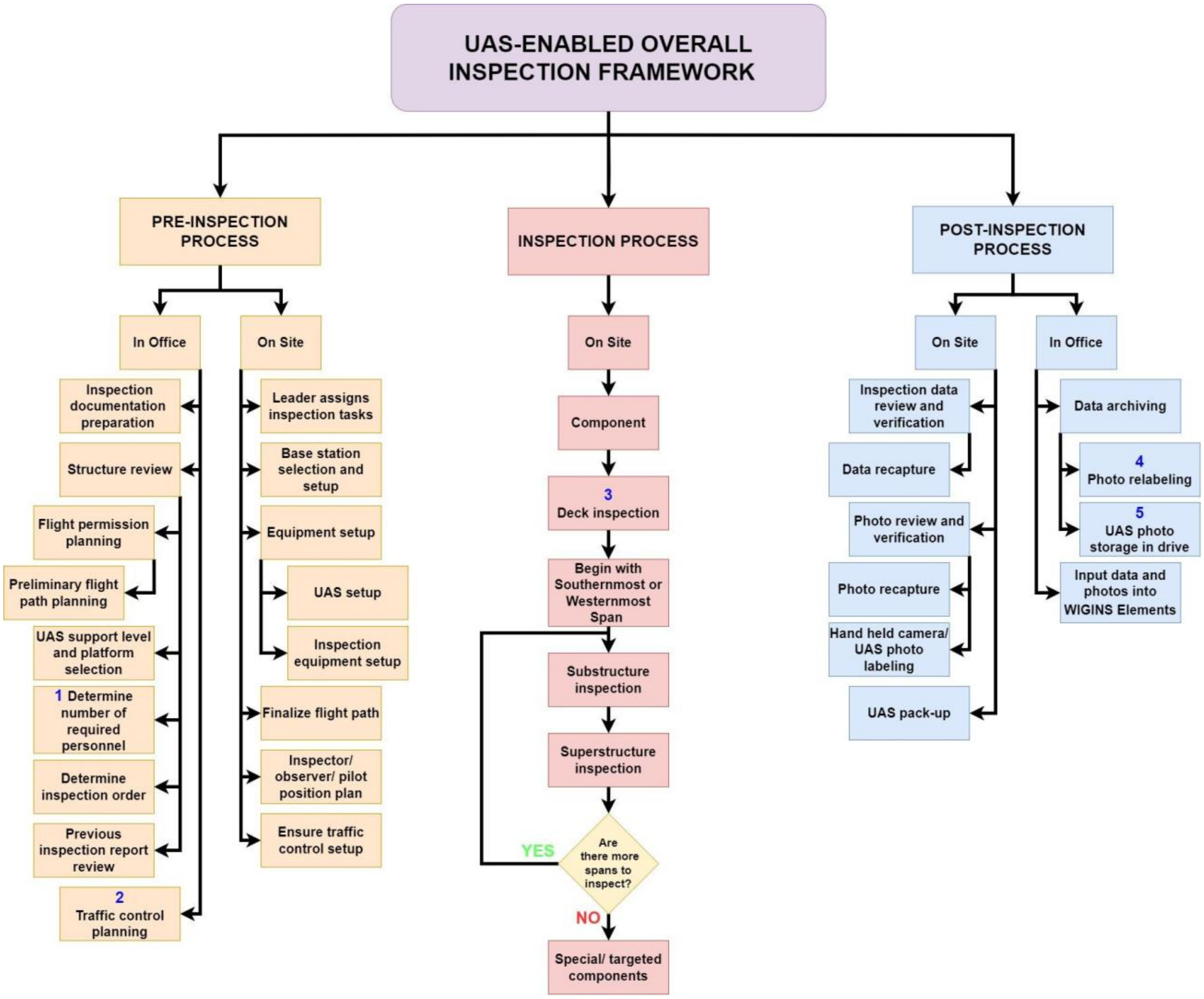
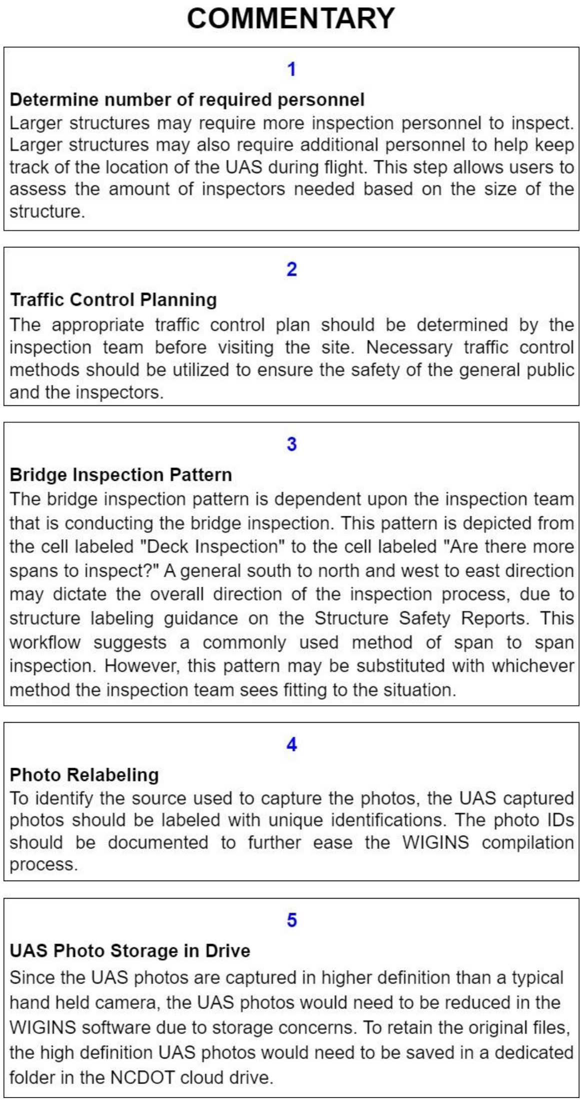


Figure 3.3: Commentary Boxes to the UAS-Enabled Overall Inspection Framework Workflow.



COMMENTARY

1

Determine number of required personnel

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Traffic Control Planning

The appropriate traffic control plan should be determined by the inspection team before visiting the site. Necessary traffic control methods should be utilized to ensure the safety of the general public and the inspectors.

3

Bridge Inspection Pattern

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Photo Relabeling

To identify the source used to capture the photos, the UAS captured photos should be labeled with unique identifications. The photo IDs should be documented to further ease the WIGINS compilation process.

5

UAS Photo Storage in Drive

Since the UAS photos are captured in higher definition than a typical hand held camera, the UAS photos would need to be reduced in the WIGINS software due to storage concerns. To retain the original files, the high definition UAS photos would need to be saved in a dedicated folder in the NCDOT cloud drive.

Figure 3.4: Commentary Boxes to the UAS-Enabled Overall Inspection Framework Workflow.

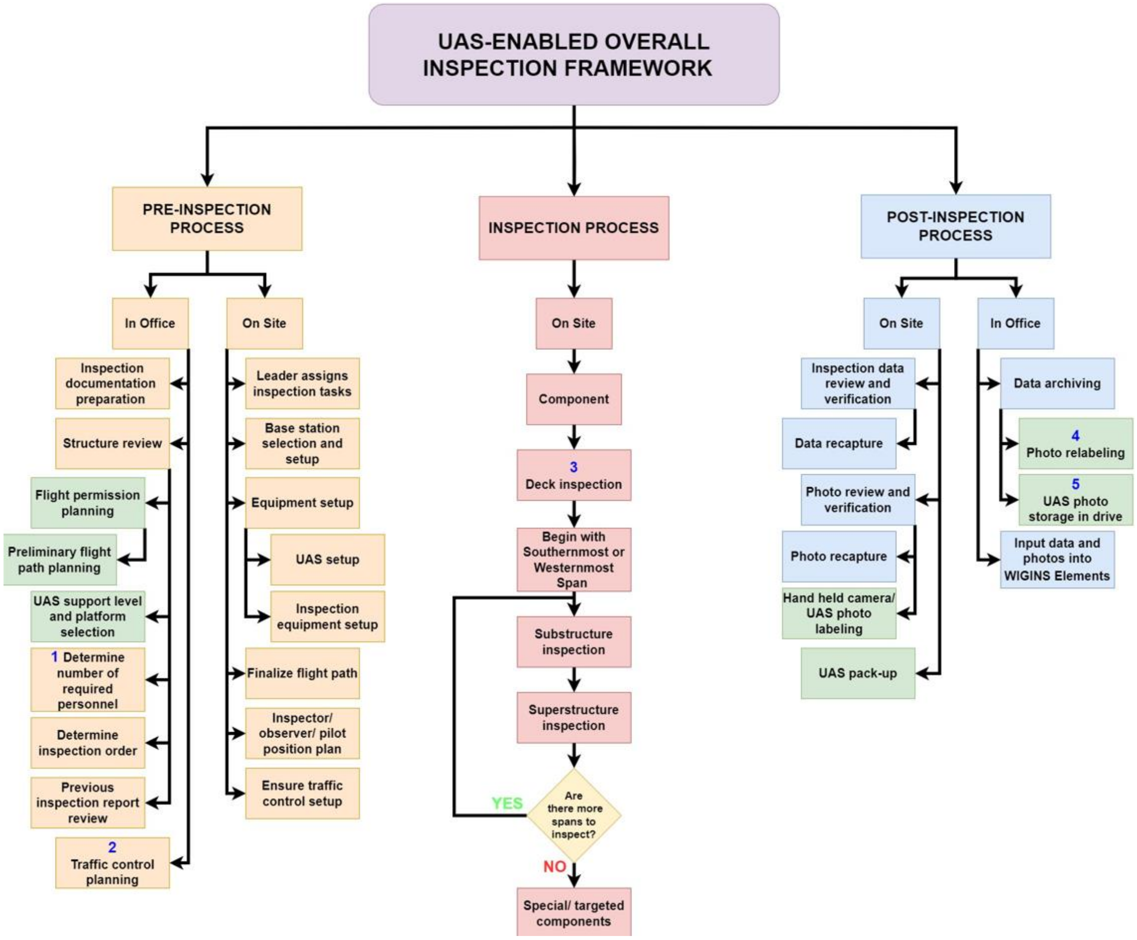
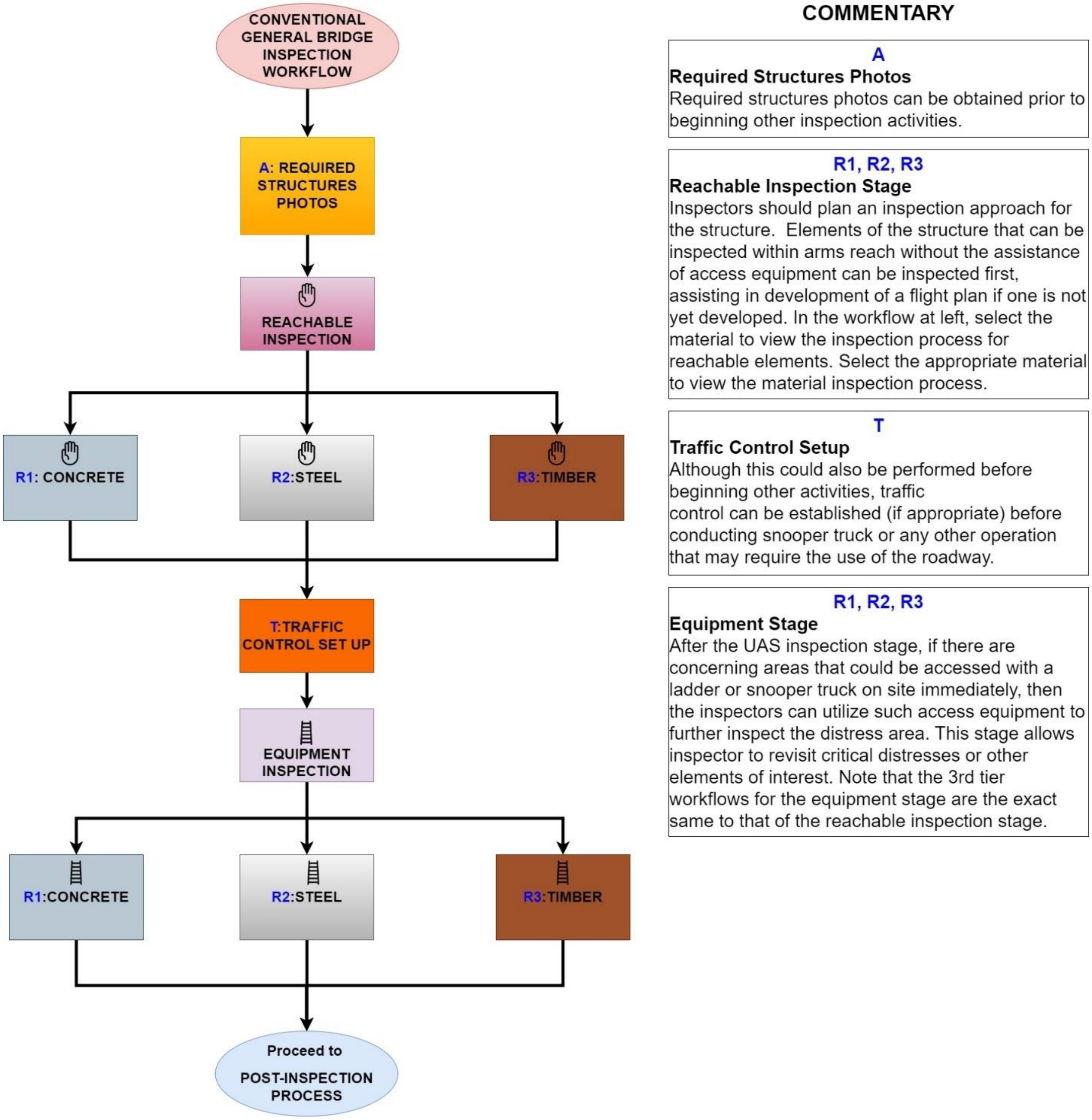


Figure 3.5: Changes to the UAS-Enabled Overall Inspection Framework Workflow (highlighted in green).

3.2.2 Level 1 2 General Bridge Inspection Workflow – Conventional, and UAS-Enabled

The inspection branch from the level 1 workflow provides users with a general inspection pattern based on the geometry of the structure. The detailed inspection stage procedure can be found in the level 2 General Bridge Inspection Workflows as described in this section. The objective of Level 2 workflows is to describe the general tasks performed during the on-site inspection process. This workflow originates from the middle branch named “Inspection Process” in the level 1 Overall Inspection Framework Workflow and ends by leading users to the “Post-Inspection Process” in the Overall Inspection Framework Workflow. Level 2 workflows introduce users to the procedures of obtaining required structure photographs, setting up traffic control, performing reachable inspection, performing non-reachable (access equipment required) inspection, and performing UAS-enabled inspection.

Two versions of the Level 2 General Bridge Inspection Workflow were developed, a conventional version (Figure 3.6) and a UAS-enabled version (Figure 3.7). The differences between these two workflows are highlighted in Figure 3.8. Throughout the field visits, most of the operations were performed conventionally, with no use of UASs. The conventional version of the General Bridge Inspection Workflow was developed based on these observations. The UAS-enabled version of this workflow was developed based on a smaller sample size of observed UAS-enabled inspections from which the understanding of the capabilities of UASs and procedural approaches and risk tolerances of the pilots were studied. Similar to the level 1 Overall Inspection Framework Workflow, the level 2 General Bridge Inspection Workflow was developed over several iterations. While the initial iterations were UAS-enabled, the last version of this workflow included a conventional version and a UAS-enabled version. All iterations and a deeper discussion on their development and evolution over the course of the project are presented in Wu (2023).



COMMENTARY

A

Required Structures Photos

Required structures photos can be obtained prior to beginning other inspection activities.

R1, R2, R3

Reachable Inspection Stage

Inspectors should plan an inspection approach for the structure. Elements of the structure that can be inspected within arms reach without the assistance of access equipment can be inspected first, assisting in development of a flight plan if one is not yet developed. In the workflow at left, select the material to view the inspection process for reachable elements. Select the appropriate material to view the material inspection process.

T

Traffic Control Setup

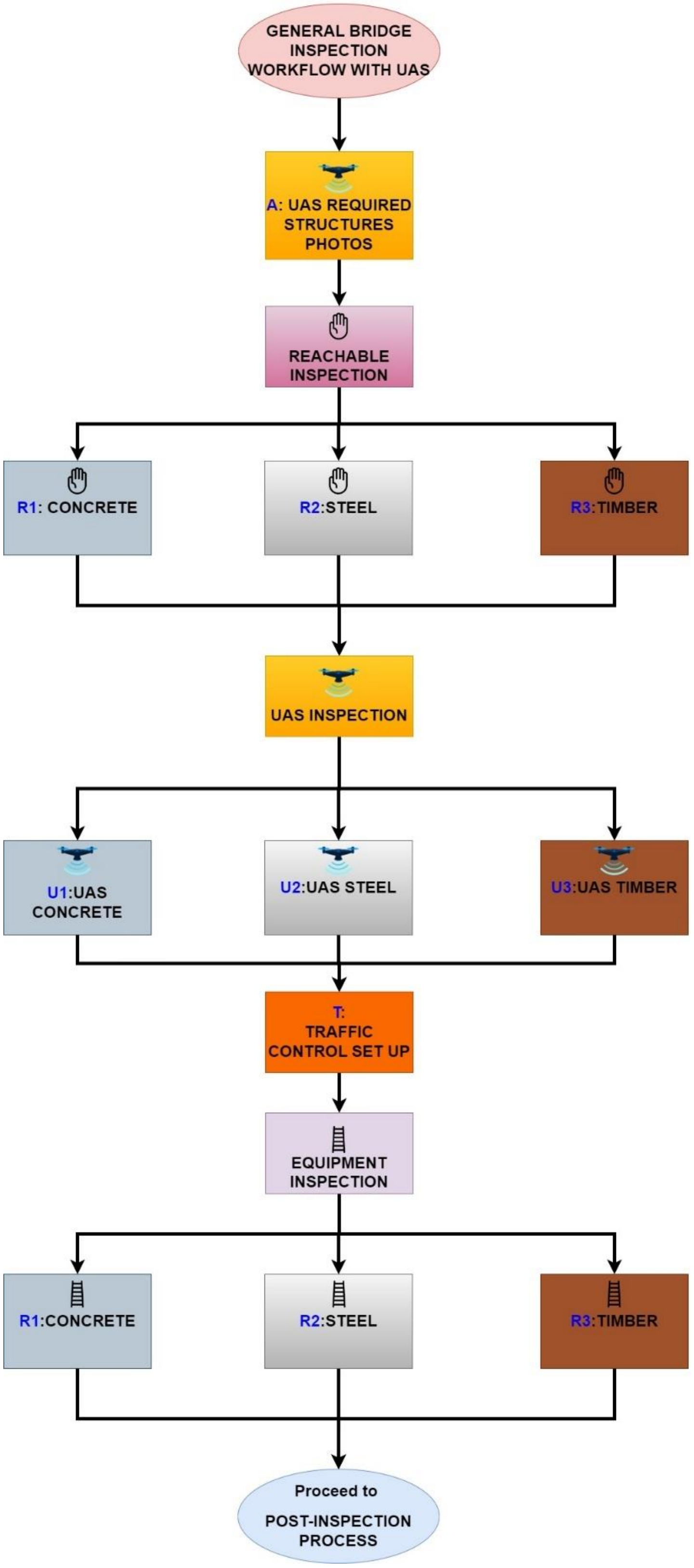
Although this could also be performed before beginning other activities, traffic control can be established (if appropriate) before conducting snooper truck or any other operation that may require the use of the roadway.

R1, R2, R3

Equipment Stage

After the UAS inspection stage, if there are concerning areas that could be accessed with a ladder or snooper truck on site immediately, then the inspectors can utilize such access equipment to further inspect the distress area. This stage allows inspector to revisit critical distresses or other elements of interest. Note that the 3rd tier workflows for the equipment stage are the exact same to that of the reachable inspection stage.

Figure 3.6: Level 2 Conventional General Bridge Inspection Workflow.



COMMENTARY

A

UAS Required Structures Photos

Required structures photos can be obtained prior to beginning other inspection activities. Enter the **UAS Required Structures Photos** workflow to begin the process.

R1, R2, R3

Reachable Inspection Stage

Inspectors should plan an inspection approach for the structure. Elements of the structure that can be inspected within arms reach without the assistance of access equipment can be inspected first,
assisting in development of a flight plan if one is not yet developed. In the workflow at left, select the material to view the inspection process for reachable elements. Select the appropriate material to view the material inspection process.

U1, U2, U3

UAS Inspection Stage

UAS-enabled bridge inspection can be performed for areas that can are not reachable and/or cannot be readily accessed. A reasonably flat and clear area should be selected for UAS takeoff and flight observation. Scan the unreachable elements of the bridge via the pre-planned flight route, or a flight route of the inspector's choosing. In the workflow at left, select the material to view the UAS-enabled material inspection process. Identify areas that will require hands-on inspection using access equipment and develop an access plan. Select the appropriate material to view the 3rd tier UAS enabled material element inspection workflows.

T

Traffic Control Setup

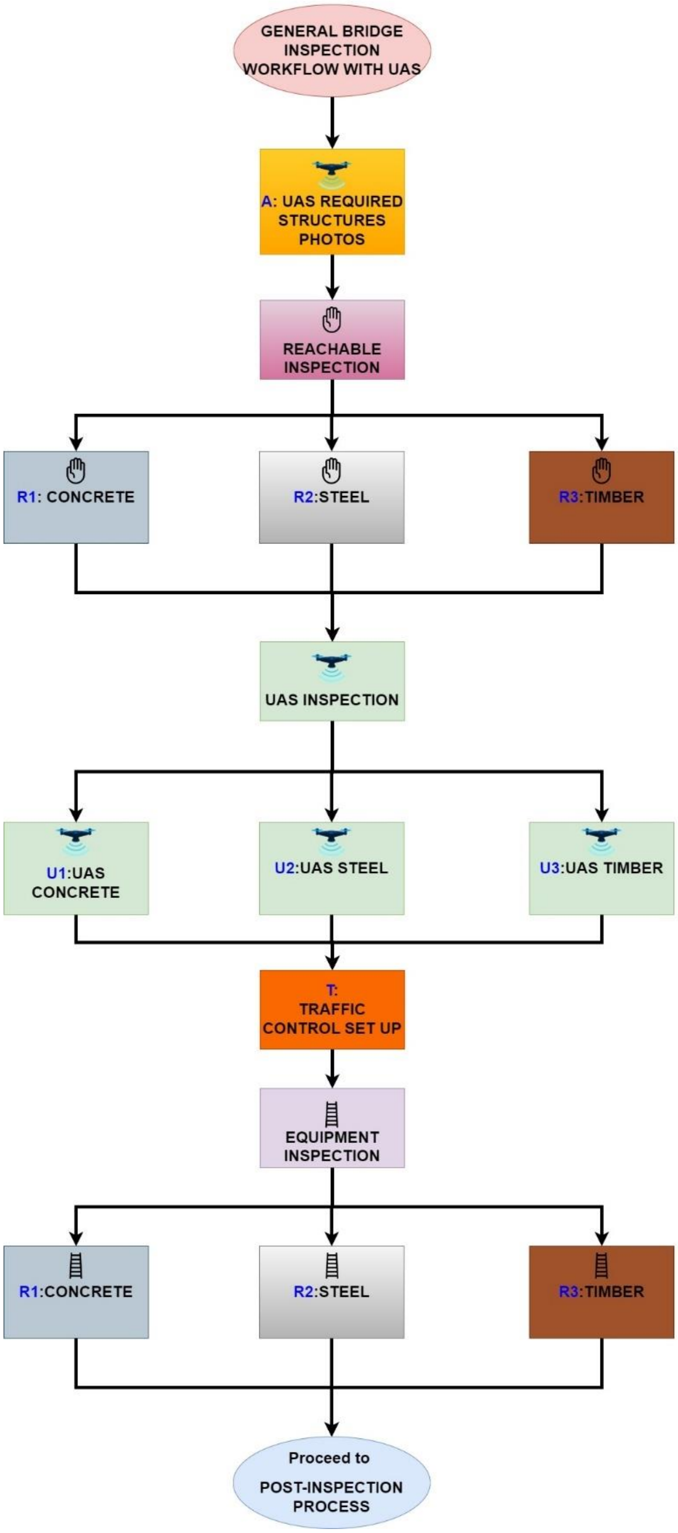
Although this could also be performed before beginning other activities, traffic control can be established (if appropriate) before conducting snooper truck or any other operation that may require the use of the roadway.

R1, R2, R3

Equipment Stage

After the UAS inspection stage, if there are concerning areas that could be accessed with a ladder or snooper truck on site immediately, then the inspectors can utilize such access equipment to further inspect the distress area. This stage allows inspector to revisit critical distresses or other elements of interest. Note that the 3rd tier workflows for the equipment stage are the exact same to that of the reachable inspection stage.

Figure 3.7: UAS-Enabled General Bridge Inspection Workflow.



COMMENTARY

A

UAS Required Structures Photos

Required structures photos can be obtained prior to beginning other inspection activities. Enter the **UAS Required Structures Photos** workflow to begin the process.

R1, R2, R3

Reachable Inspection Stage

Inspectors should plan an inspection approach for the structure. Elements of the structure that can be inspected within arms reach without the assistance of access equipment can be inspected first,

assisting in development of a flight plan if one is not yet developed. In the workflow at left, select the material to view the inspection process for reachable elements. Select the appropriate material to view the material inspection process.

U1, U2, U3

UAS Inspection Stage

UAS-enabled bridge inspection can be performed for areas that can are not reachable and/or cannot be readily accessed. A reasonably flat and clear area should be selected for UAS takeoff and flight observation. Scan the unreachable elements of the bridge via the pre-planned flight route, or a flight route of the inspector's choosing. In the workflow at left, select the material to view the UAS-enabled material inspection process. Identify areas that will require hands-on inspection using access equipment and develop an access plan. Select the appropriate material to view the 3rd tier UAS enabled material element inspection workflows.

T

Traffic Control Setup

Although this could also be performed before beginning other activities, traffic control can be established (if appropriate) before conducting snooper truck or any other operation that may require the use of the roadway.

R1, R2, R3

Equipment Stage

After the UAS inspection stage, if there are concerning areas that could be accessed with a ladder or snooper truck on site immediately, then the inspectors can utilize such access equipment to further inspect the distress area. This stage allows inspector to revisit critical distresses or other elements of interest. Note that the 3rd tier workflows for the equipment stage are the exact same to that of the reachable inspection stage.

Figure 3.8: Differences Between the Conventional UAS-Enabled (Right) Level 2 Workflows (highlighted in green)

During the field observations, it was typically observed that the inspection team would first capture the required photographs, as advised by the SMU Inspection Manual. Different angles of the structure would be photographed to complete this task. During this stage, users are directed to a level 3 workflow named "UAS Required Structure Photos Workflow." This workflow guides users to capture the required photographs using a UAS. If the user chooses to capture the photographs with a handheld camera, then this workflow may be neglected with these required photographs captured conventionally.

After completing this task, the inspection team would begin inspecting components and elements of the bridge that are within arm's reach without access equipment. If an element only requires visual confirmation, then it would also be inspected during this stage. These inspection tasks are named "Reachable Inspections" in these workflows, since these elements could be inspected without the need for access equipment such as ladders, boats, snooper trucks, or other equipment. After the "Reachable Inspection" task, a series of level 3 workflows named "Concrete," "Steel," and "Timber," are introduced to guide users on the inspection of the three main material types mentioned in the upcoming section.

Once the reachable inspections are completed, the conventional workflow prompts users to perform traffic control setup, if necessary. If only a ladder is required to inspect all other areas of the bridge deemed as not reachable, then traffic control may not be needed. If a snooper truck or box truck is required, then users are prompted to perform traffic control. For the UAS-enabled version of this workflow, once the reachable inspection is completed, users are prompted to perform a UAS inspection, instead of immediately preparing for the setup of traffic control. This step allows users to perform visual inspections with a UAS on the items that are not normally visible to the inspectors on ground. The use of the UAS would help identify areas of the bridge that are not reachable but may require inspectors to perform hands-on inspection due to evidence of potential distress. For the UAS-enabled version of this workflow, these areas would be further inspected during the "access equipment stage."

During an inspection on access equipment, the way inspectors perform tasks for each material is identical to the approach performed during reachable inspections on the material. Therefore, for the conventional version of the General Bridge Inspection Workflow, the "reachable" and "access equipment" stages incorporate identical level 3 material inspection workflows. The final iteration of the workflows introduced the addition of the "Required Structures Photos" task, as well as the "Traffic Control Set Up" task. The "Required Structures Photos" task in the conventional version of the workflow serves only as a prompt for users to capture the required angles of any structure, whereas the "UAS Required Structures Photos" cell in the UAS-enabled version of the workflow directs users to a level 3 workflow dedicated to guidance for capturing the required photographs using a UAS.

3.2.3 Level 3 – Element Inspection Workflows and UAS Required Structure Photos Workflow- Conventional and UAS-Enabled

The level 3 workflows contain diagnostic decision trees based on different material types, as well as guidance on how UASs could be used to obtain the required photographs as mentioned in the previous section. These workflows are extensions of the level 2 General Bridge Inspection Workflows. These element inspection workflows focus on three main types of materials: concrete, steel, and timber, the most predominant materials used for bridge construction in the state of North Carolina (Snoke 2022). According to InfoBridge, a FHWA website that provides data based on the NBI, out of 18,817 bridges in North Carolina, 18,422 of them have main spans constructed by one of the three materials mentioned above (FHWA 2023). As mentioned in the previous section, only concrete and steel bridge inspection operations were observed. A set of timber workflows were created to meet the needs of the NCDOT by using the guidance in the NCDOT Manual for Bridge Element Inspection and the SMU Inspection Manual. The element inspection workflows were developed to assist inspectors in classifying and recording distresses via conventional methods and the UAS-enabled method. The conventional methods are referred to as the "Reachable Element Inspection" due to the fact that the main difference between a conventional inspection and a UAS inspection is whether an element is within reach for the inspectors without access equipment.

It was recognized that the vast range of case-specific considerations and decision-making required to diagnose the condition of a specific material would be difficult to encompass within a single workflow. One of the main challenges was to identify the appropriate depth and detail of the workflow decision trees without overcrowding the workflow space or becoming confusing or overburdensome to an inspector. Overcrowding the workflow or providing too much detailed information may lead to user fatigue and could limit the inspector in using previous experience to help inform the inspection process. Considering that the level 3 workflows are most applicable in the field, simplicity is critical to an effective workflow. Therefore, it was determined that the element inspection workflows would focus on the distress measurement and recording processes, with only the diagnosing processes associated with "Critical finding" items explicitly called out. The combination of distress identification, distress measurement, Critical Finding classification, and distress recording was determined to be the optimal amount of detail on the inspection tasks contained within any single workflow.

The overall logic behind diagnosing distresses was observed to be consistent across different material types. Therefore, although there are three sets of material inspection workflows (conventional and UAS-enabled versions for each of the three material workflows), they are based on the same inspection logic. The workflows focus on helping users identify the most severe classification of distresses as stated by the SMU Inspection Manual, which are "Critical Findings" (NCDOT 2018). Although the standard operating procedure states that distresses categorized by the inspectors as either Critical Finding or Priority Maintenance are to be submitted to the SMU for review through the WIGINS Elements software, these workflows allow inspectors to quickly identify Critical Finding distresses, since they may require more attention due to the implied risk to public safety.

Upon approaching a distress, the first task for an inspector is to identify the type of material in which the distress has occurred. As mentioned previously, different materials may be present on the same bridge, so the proper element inspection workflow should be utilized to correctly assess the distress. Once the proper element inspection workflow is used, the inspector would then categorize the distress based on its type. Different materials have different distress types and the classification of severity for different distress types is covered by the SMU Inspection Manual. The element inspection workflows feature a series of questions to help inspectors determine whether a distress should be classified as Critical Finding or not. If a distress is determined to be a Critical Finding, then the inspector would immediately be cognizant of the situation and may choose to escalate the response to the distress. If a distress is deemed as either Priority Maintenance or routine maintenance, then a typical reporting process would be followed.

After the identification of the distress severity, the workflows ask the inspectors to determine whether the distress is a pre-existing distress. If a certain distress existed prior to the current inspection cycle, there would be information on the distress in the previous Structure Safety Report. The objective of this task is to determine whether a pre-existing distress has worsened. The worsening of a distress would most likely be manifest as an increase in size or depth of the distress. Inspectors would make note of the pre-existing distress in the WIGINS Elements software.

If the distress is new (not pre-existing), then the inspector would begin the process of recording relevant distress information. The workflow first prompts users to obtain a photograph for recording purposes. A reasonable number of photographs to represent different distresses are expected to be inserted into the WIGINS Elements software, and this action in the workflows would guide inspectors through this task. After obtaining the photographs of the distress, the workflows then prompt users to perform the recording of distress dimensions and information, as well as the photograph ID to better help inspectors reference the photographs to their corresponding distresses when compiling the Structure Safety Report in the WIGINS Elements software.

The observation of bridge inspection operations was performed for concrete and steel structures, therefore the conventional and UAS versions of these workflows were developed first. Figures 3.9, 3.10, and 3.11 present the conventional Concrete Element Inspection Workflow along with its comment boxes. Figures 3.12, 3.13, and 3.14 present the UAS-Enabled Concrete Element Inspection Workflow along with its comment boxes. Figure 3.15 shows the difference between the conventional and UAS-enabled inspection of concrete elements. Earlier iterations and a deeper discussion on development of these final workflows is presented in Wu (2023).

The first challenge identified for a UAS-enabled concrete inspection was for UASs to inspect patches and delamination. Typically, these distress types require inspectors to put their hands (or tools such as hammers or pocket knives) on the distresses. The perimeter of a patch and a delamination would be inspected by the inspectors brushing away debris with their hands. If the perimeter of a patch or delamination appears to be flaking, inspectors will sound the patch or delamination with a hammer to listen for differences in the sound echo generated by the patched concrete versus concrete that surrounds the patch. Because of the need for hands-on inspection for these two types of distresses, the workflow prompts users to use the UAS to perform visual inspection initially, followed by a hands-on inspection during the access equipment inspection stage of the operation.

The UAS-Enabled versions of the workflows take into consideration the capabilities of the UASs, as well as their abilities to perform human tasks. The overall finding through the field observations led to the conclusion that UASs serve primarily as mobile cameras, offering inspectors the ability to view distresses from afar. However, it was determined that the UASs should only be used to perform visual inspections. If certain distresses require hands-on inspection, inspectors could utilize UASs to locate those distress locations and schedule access equipment to get closer to the distress at a later time. To optimize the development process of the UAS-enabled material inspection workflows, the initial stages of this work focused on the development of the concrete workflow. After a few refinements of the concrete workflow, steel and timber workflows were then developed based on the template and logic that was used on the concrete workflow.

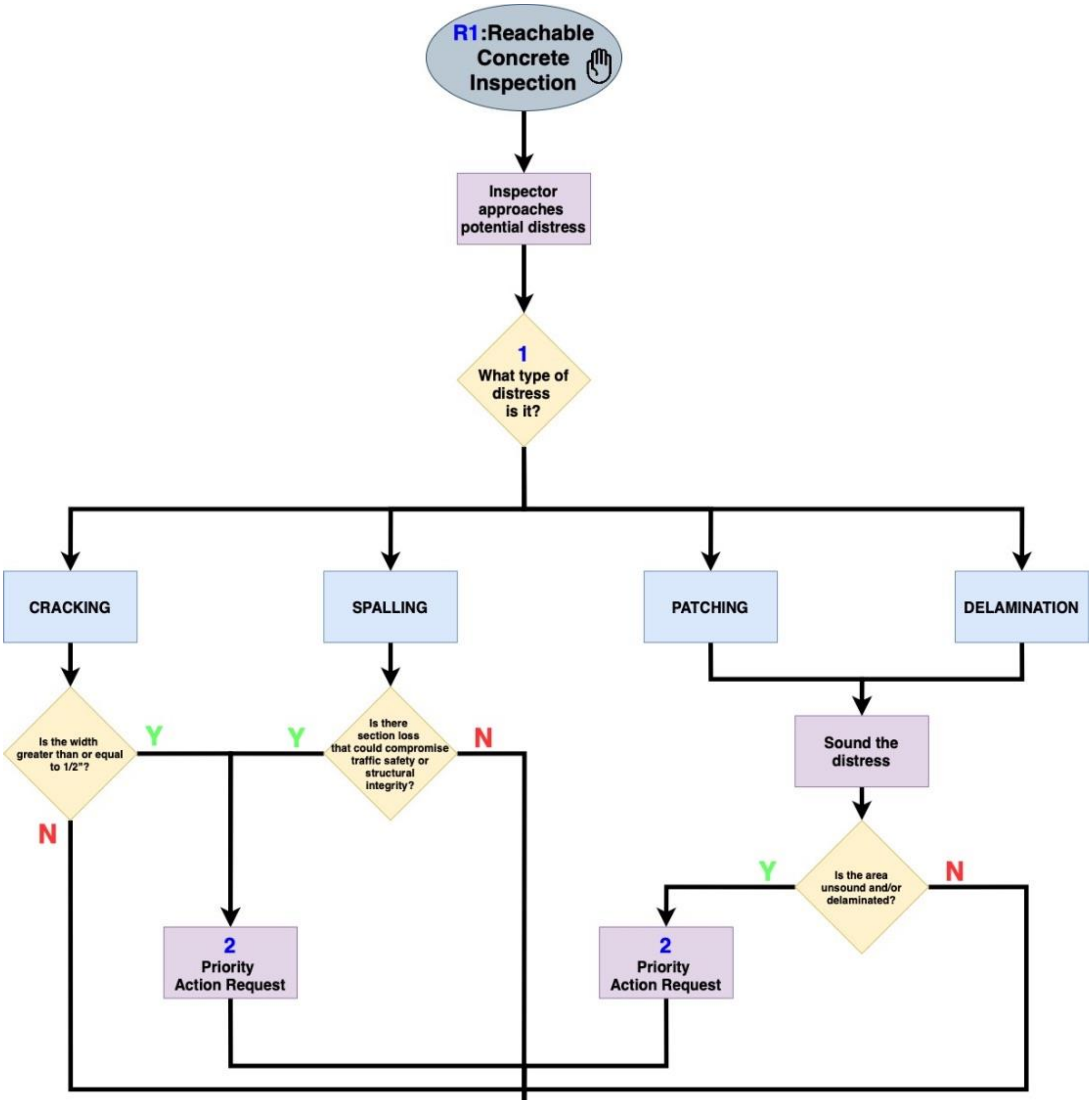


Figure 3.9: Conventional Concrete Element Inspection Workflow- Part 1 (upper portion).

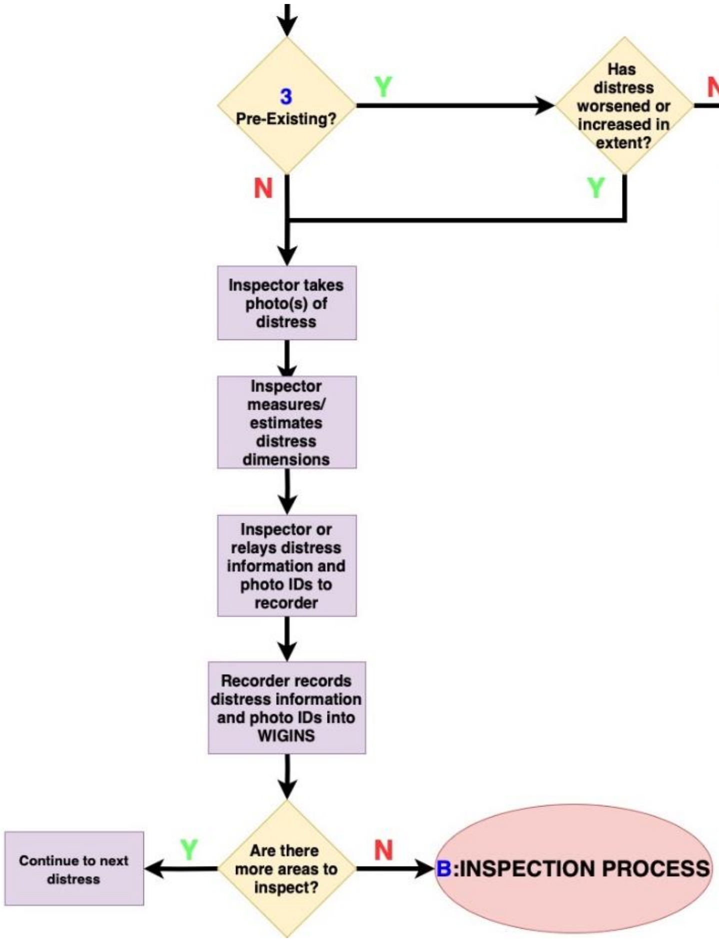
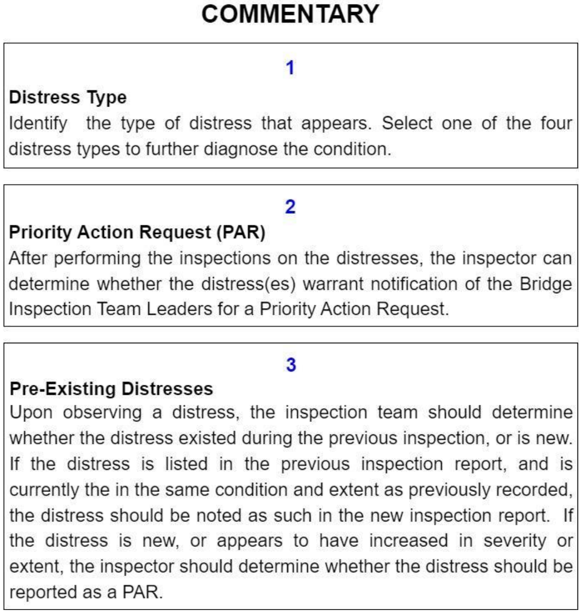


Figure 3.10: Conventional Concrete Element Inspection Workflow- Part 2 (lower portion).



COMMENTARY

1

Distress Type

Identify the type of distress that appears. Select one of the four distress types to further diagnose the condition.

2

Priority Action Request (PAR)

After performing the inspections on the distresses, the inspector can determine whether the distress(es) warrant notification of the Bridge Inspection Team Leaders for a Priority Action Request.

3

Pre-Existing Distresses

Upon observing a distress, the inspection team should determine whether the distress existed during the previous inspection, or is new. If the distress is listed in the previous inspection report, and is currently the in the same condition and extent as previously recorded, the distress should be noted as such in the new inspection report. If the distress is new, or appears to have increased in severity or extent, the inspector should determine whether the distress should be reported as a PAR.

Figure 3.11: Commentary Boxes to the Conventional Concrete Element Inspection Workflow.

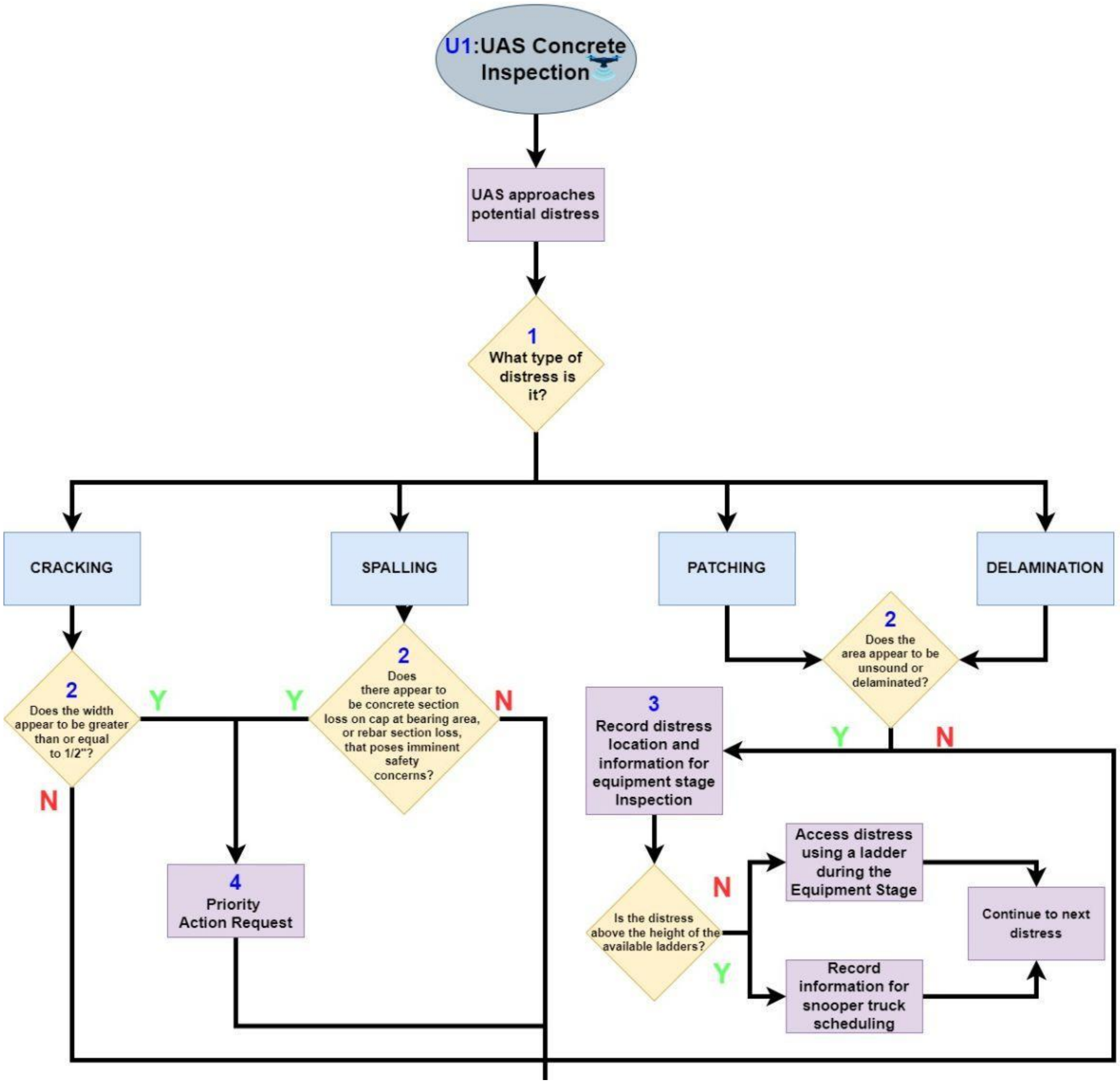


Figure 3.12: UAS-Enabled Concrete Element Inspection Workflow- Part 1 (upper portion).

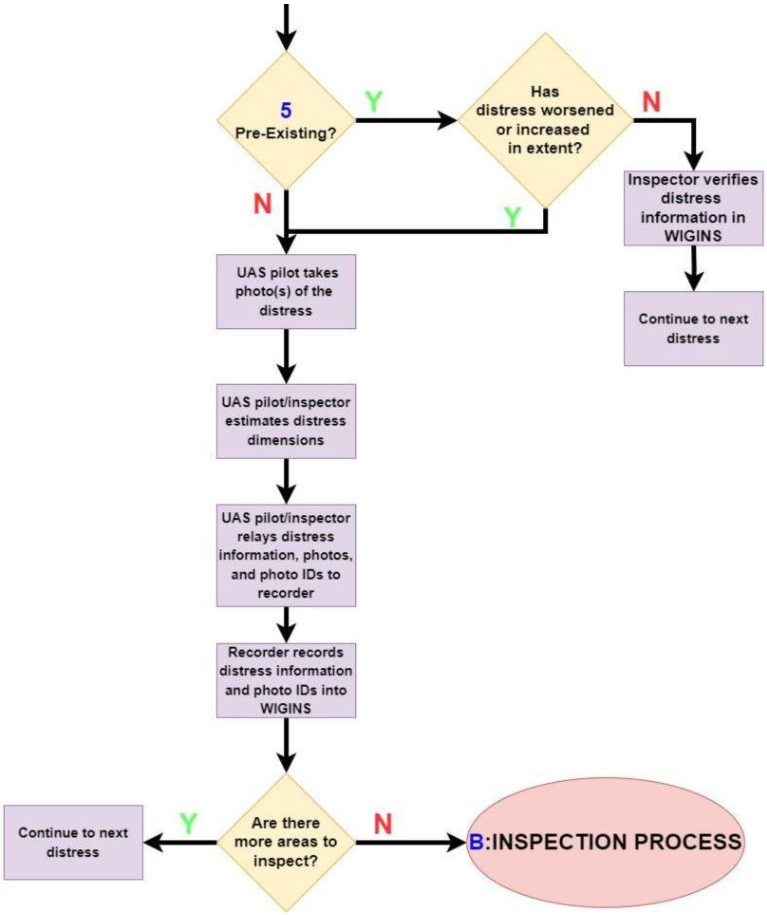
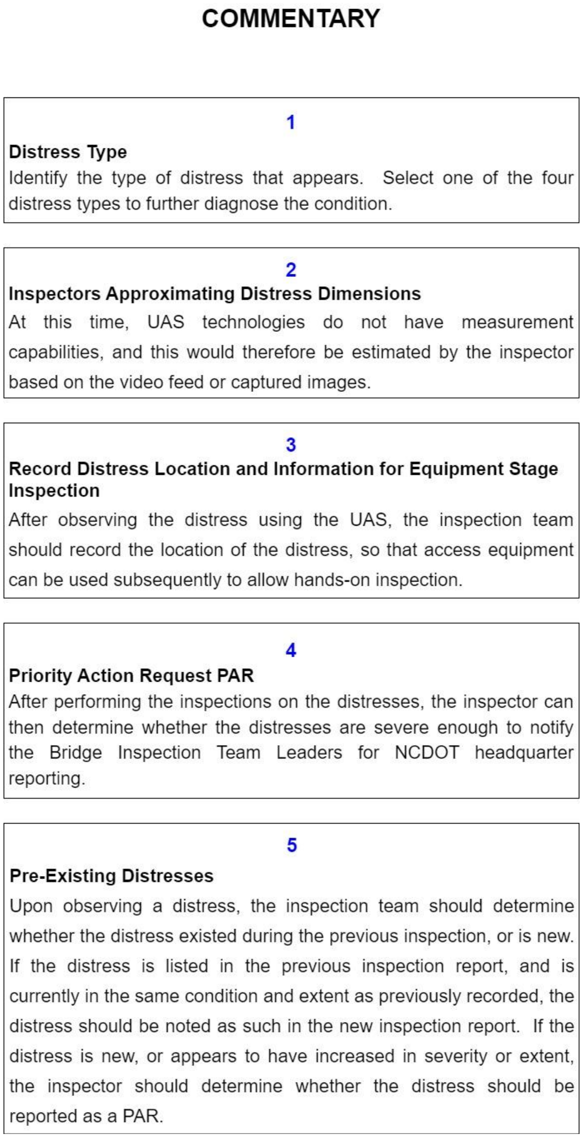


Figure 3.13: UAS-Enabled Concrete Element Inspection Workflow- Part 2 (lower portion).



COMMENTARY

1

Distress Type

Identify the type of distress that appears. Select one of the four distress types to further diagnose the condition.

2

Inspectors Approximating Distress Dimensions

At this time, UAS technologies do not have measurement capabilities, and this would therefore be estimated by the inspector based on the video feed or captured images.

3

Record Distress Location and Information for Equipment Stage Inspection

After observing the distress using the UAS, the inspection team should record the location of the distress, so that access equipment can be used subsequently to allow hands-on inspection.

4

Priority Action Request PAR

After performing the inspections on the distresses, the inspector can then determine whether the distresses are severe enough to notify the Bridge Inspection Team Leaders for NCDOT headquarter reporting.

5

Pre-Existing Distresses

Upon observing a distress, the inspection team should determine whether the distress existed during the previous inspection, or is new. If the distress is listed in the previous inspection report, and is currently in the same condition and extent as previously recorded, the distress should be noted as such in the new inspection report. If the distress is new, or appears to have increased in severity or extent, the inspector should determine whether the distress should be reported as a PAR.

Figure 3.14: Commentary Boxes to the UAS-Enabled Concrete Element Inspection Workflow.

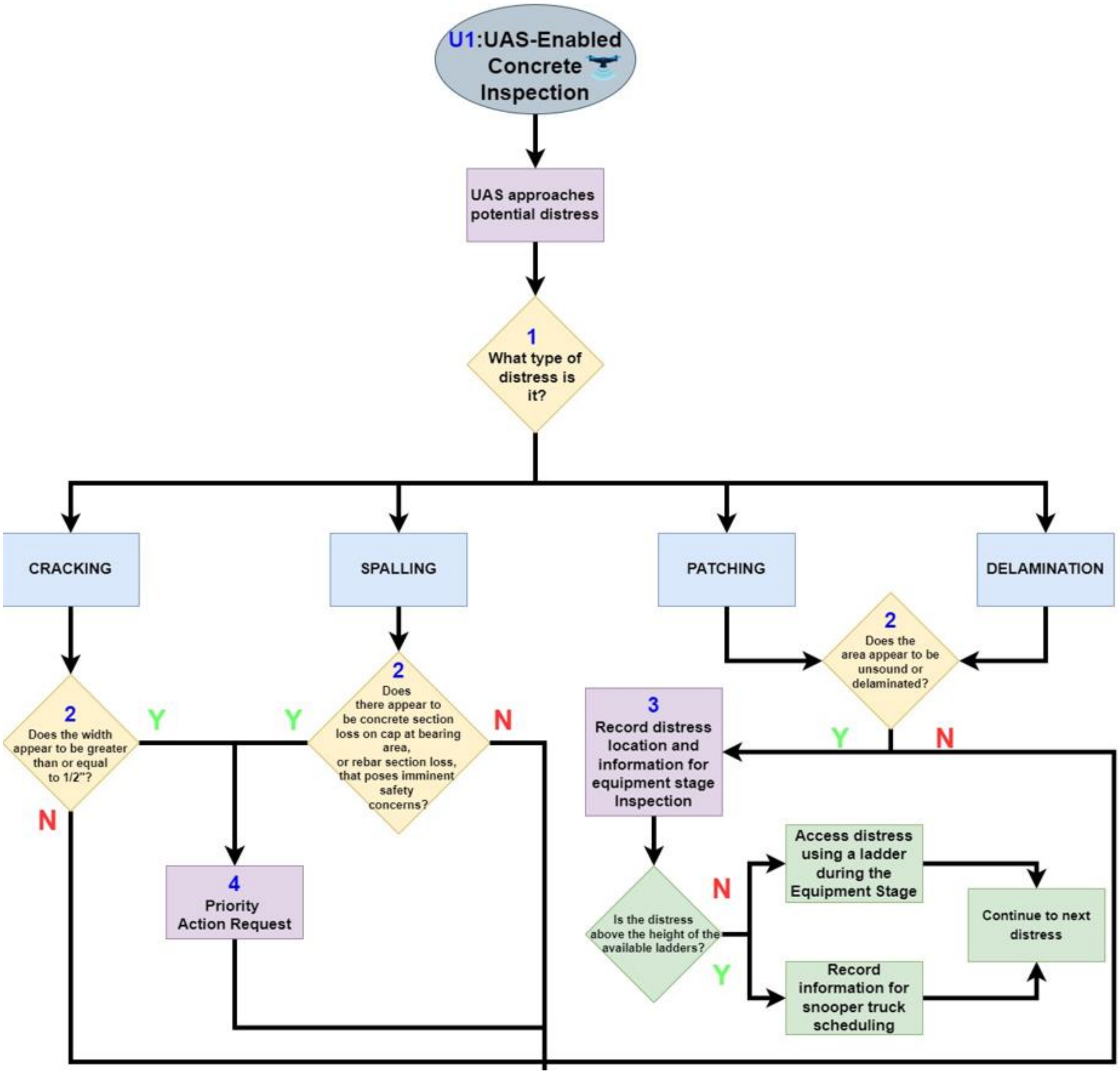


Figure 3.15: Top Portion of UAS-Enabled Concrete Element Inspection Workflow with Changes from Conventional Inspection Highlighted in Green.

Once the final iteration of the UAS-Enabled Concrete Element Inspection Workflow had been developed, the steel and timber versions were developed using the same logic, since there are many process similarities when inspecting different distress types in different materials. Figures 3.16 and 3.17 present the Conventional Steel Element Inspection Workflows, while Figure 3.18 shows the corresponding commentary boxes. Figures 3.19 and 3.20 present the UAS-enabled Steel Element Inspection Workflows while Figure 3.21 presents the corresponding commentary boxes. The differences between the conventional and UAS-enabled versions of the workflows are shown in Figure 3.22.

Of note in the Steel Element Inspection workflows, non-redundant steel tension members (NSTM) (formerly fracture critical members) must be inspected hands-on, and the UAS may only be used for documentation. A note regarding this need has been added to Figures 3.18, 3.22, and 3.24.

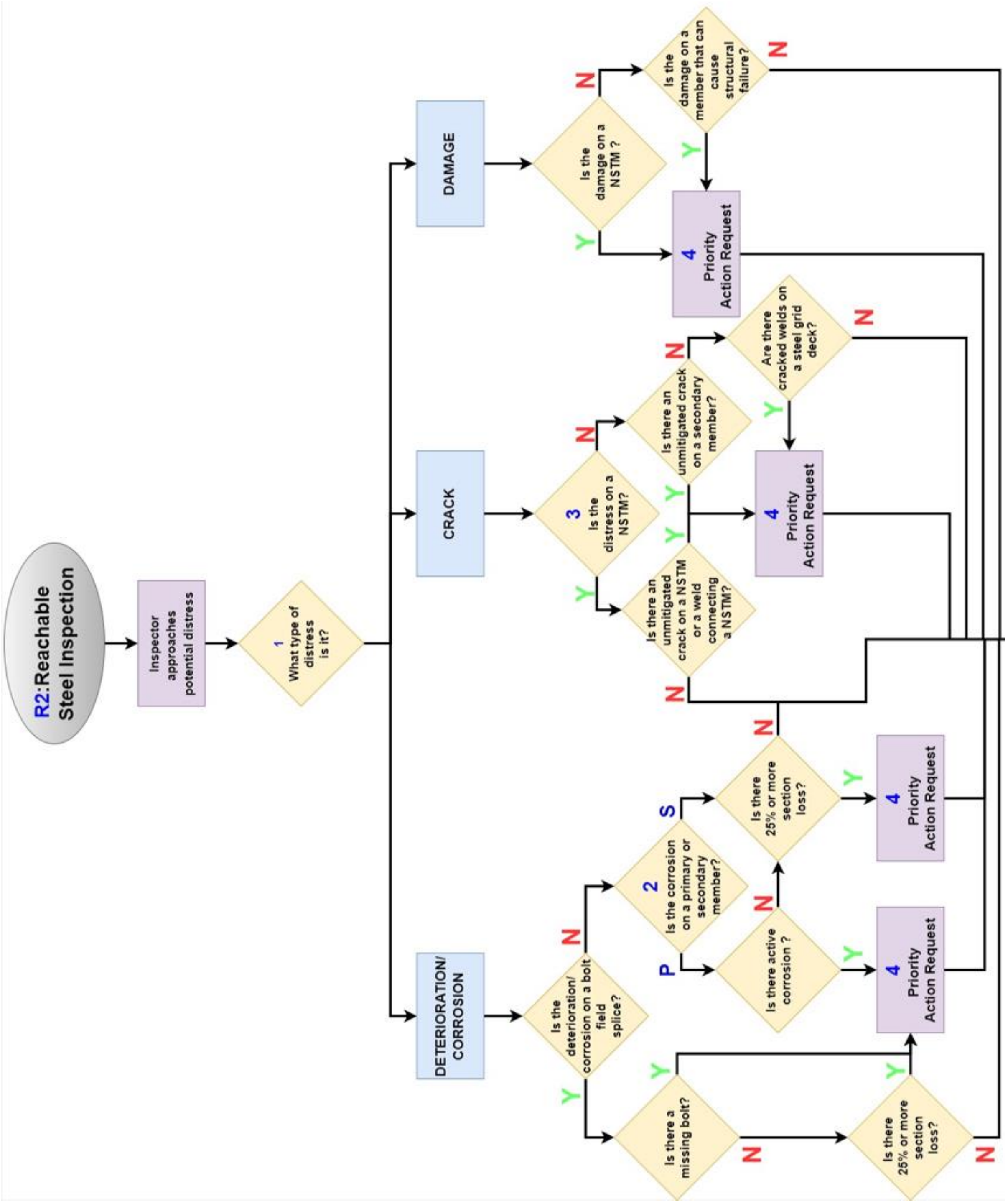


Figure 3.16: Conventional Steel Element Inspection Workflow- Part 1 (upper portion).

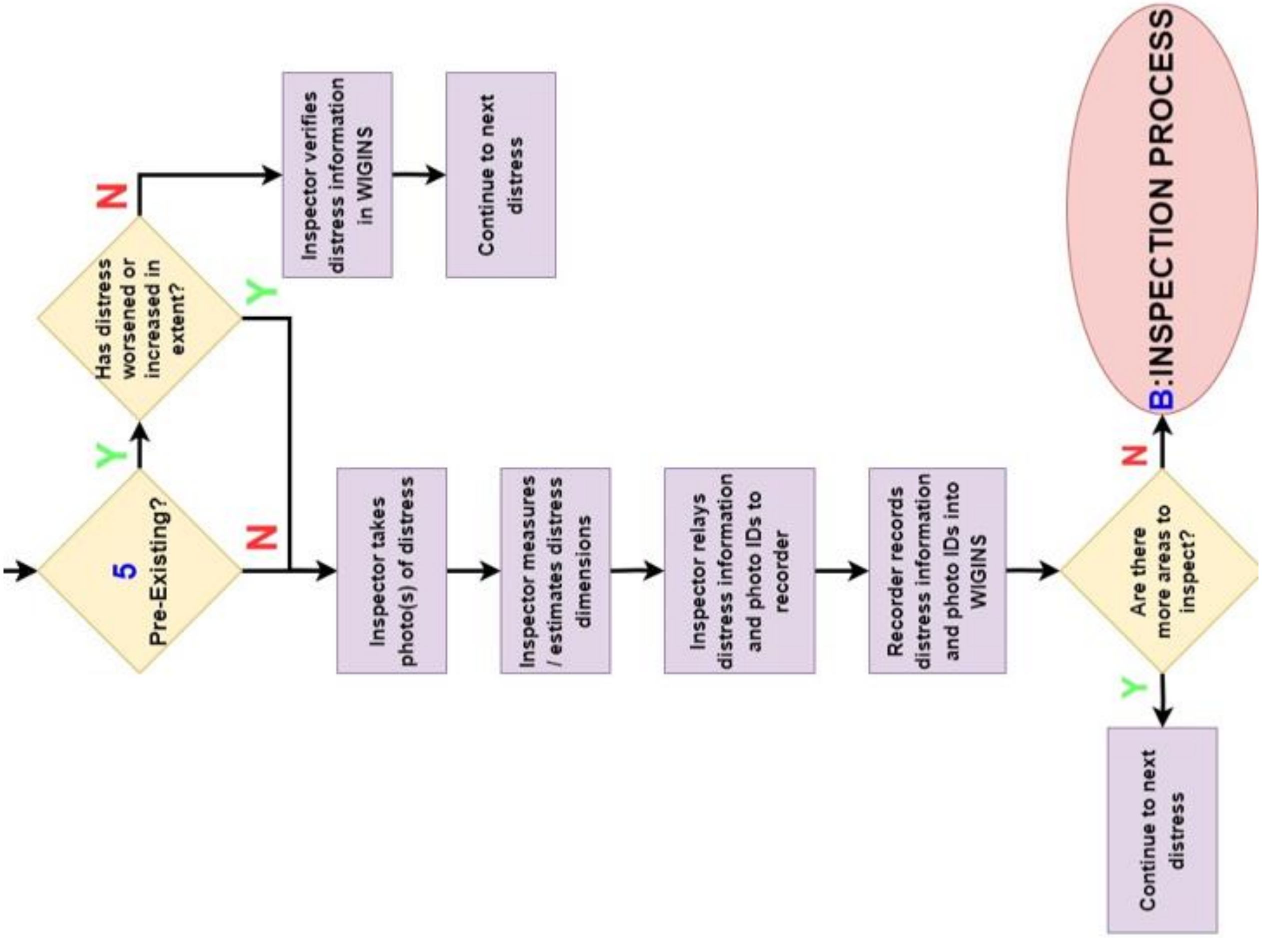
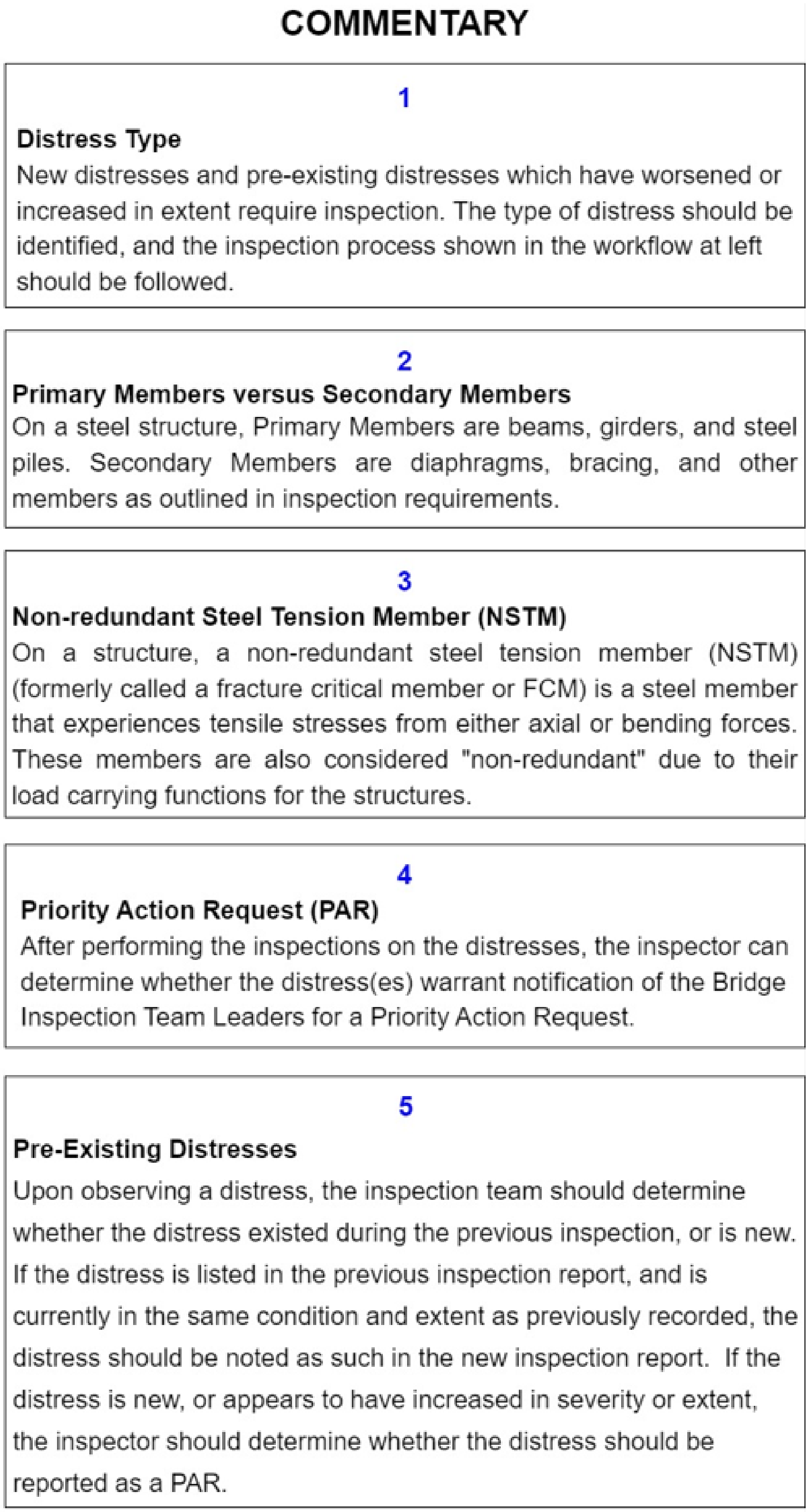


Figure 3.17: Conventional Steel Element Inspection Workflow- Part 2 (lower portion).



COMMENTARY

1

Distress Type

New distresses and pre-existing distresses which have worsened or increased in extent require inspection. The type of distress should be identified, and the inspection process shown in the workflow at left should be followed.

2

Primary Members versus Secondary Members

On a steel structure, Primary Members are beams, girders, and steel piles. Secondary Members are diaphragms, bracing, and other members as outlined in inspection requirements.

3

Non-redundant Steel Tension Member (NSTM)

On a structure, a non-redundant steel tension member (NSTM) (formerly called a fracture critical member or FCM) is a steel member that experiences tensile stresses from either axial or bending forces. These members are also considered "non-redundant" due to their load carrying functions for the structures.

4

Priority Action Request (PAR)

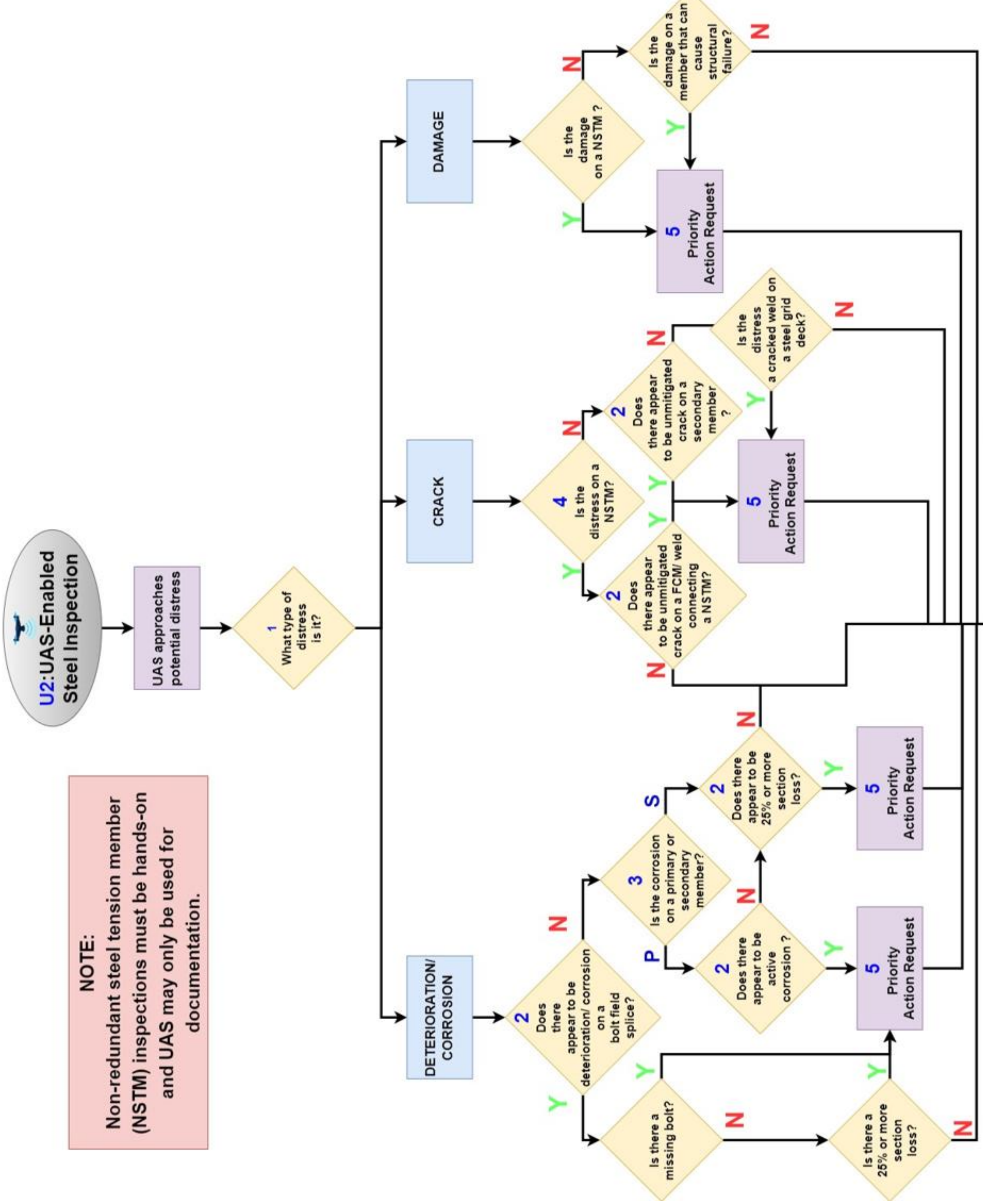
After performing the inspections on the distresses, the inspector can determine whether the distress(es) warrant notification of the Bridge Inspection Team Leaders for a Priority Action Request.

5

Pre-Existing Distresses

Upon observing a distress, the inspection team should determine whether the distress existed during the previous inspection, or is new. If the distress is listed in the previous inspection report, and is currently in the same condition and extent as previously recorded, the distress should be noted as such in the new inspection report. If the distress is new, or appears to have increased in severity or extent, the inspector should determine whether the distress should be reported as a PAR.

Figure 3.18: Commentary Boxes to the Conventional Steel Element Inspection Workflow.



NOTE:

Non-redundant steel tension member (NSTM) inspections must be hands-on and UAS may only be used for documentation.

Figure 3.19: UAS-Enabled Steel Element Inspection Workflow- Part 1 (upper portion).

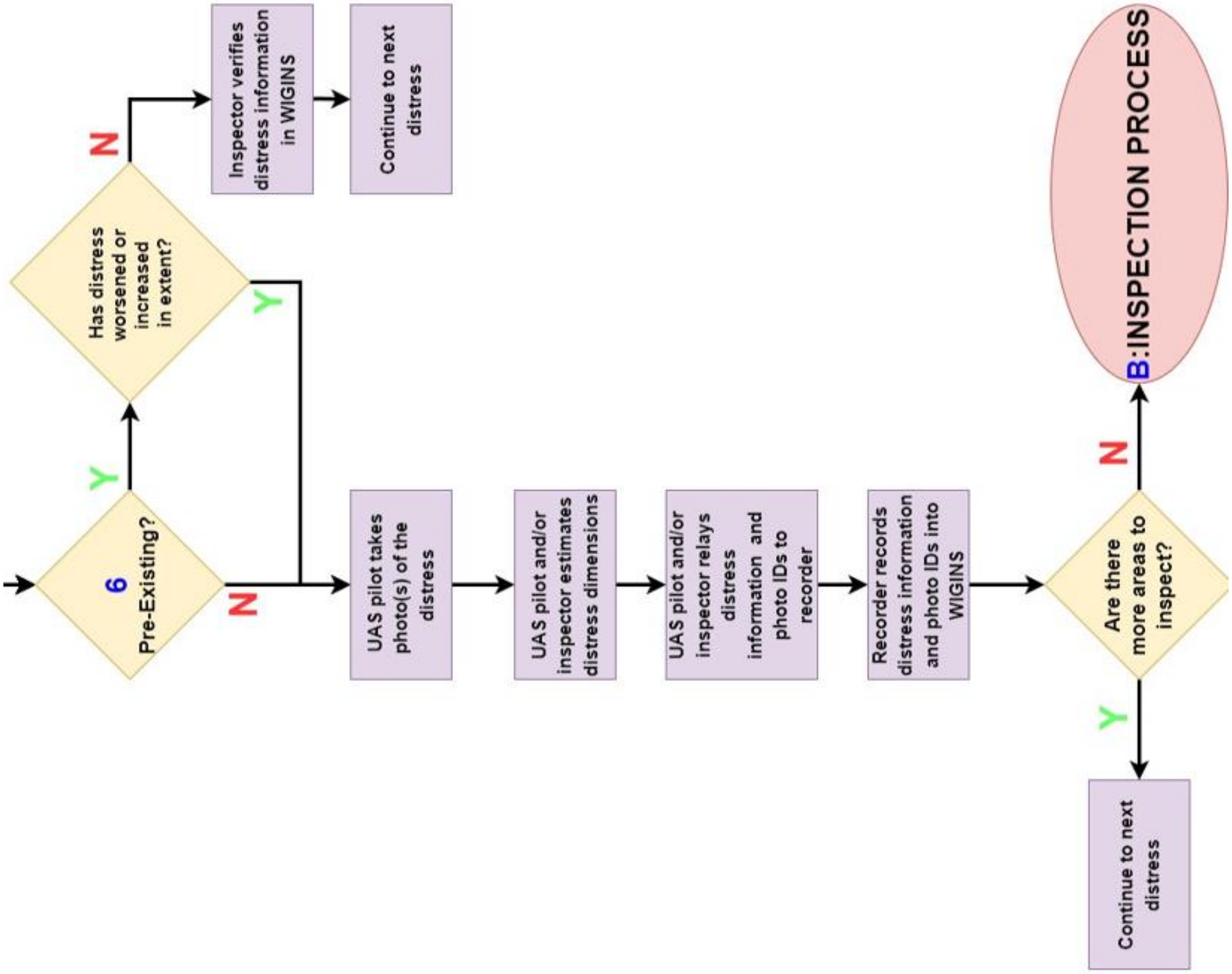
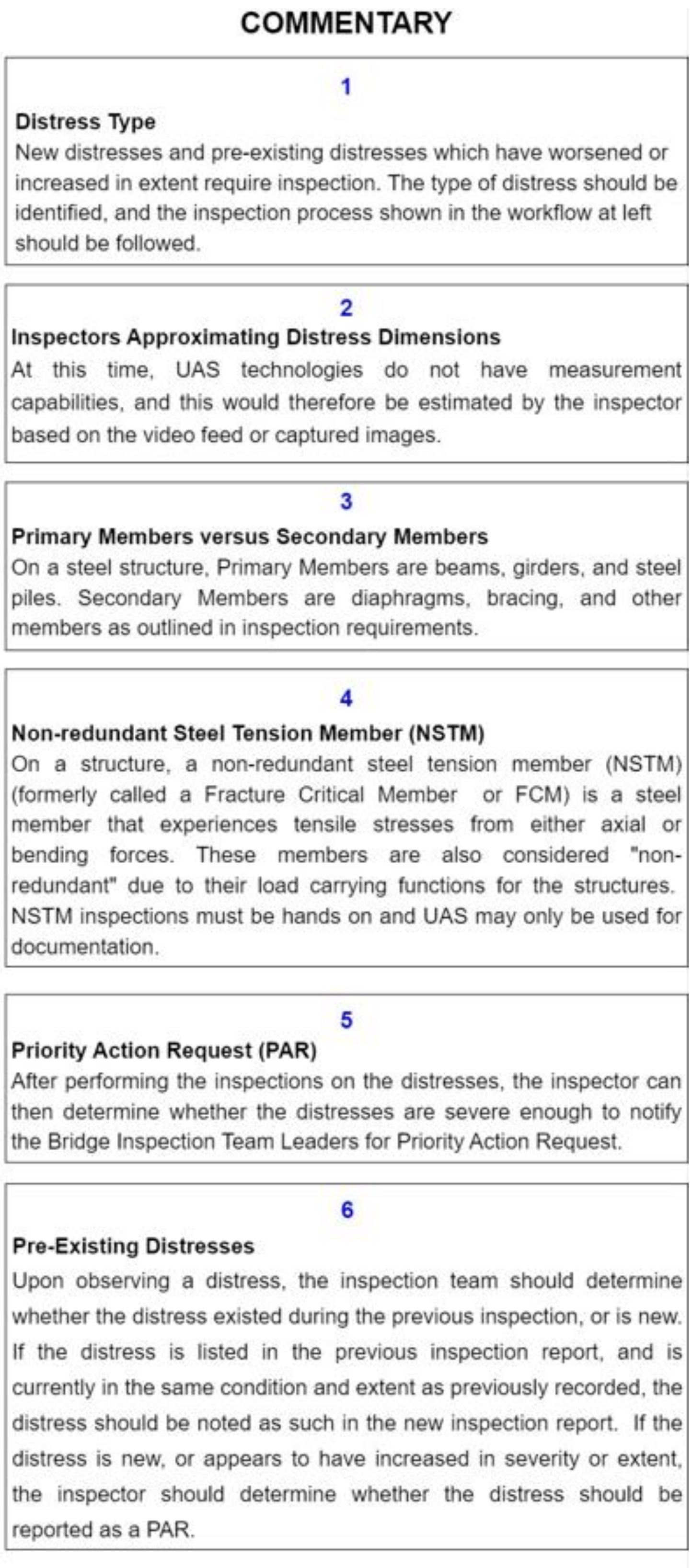


Figure 3.20: UAS-Enabled Steel Element Inspection Workflow- Part 2 (lower portion).



COMMENTARY

1

Distress Type

New distresses and pre-existing distresses which have worsened or increased in extent require inspection. The type of distress should be identified, and the inspection process shown in the workflow at left should be followed.

2

Inspectors Approximating Distress Dimensions

At this time, UAS technologies do not have measurement capabilities, and this would therefore be estimated by the inspector based on the video feed or captured images.

3

Primary Members versus Secondary Members

On a steel structure, Primary Members are beams, girders, and steel piles. Secondary Members are diaphragms, bracing, and other members as outlined in inspection requirements.

4

Non-redundant Steel Tension Member (NSTM)

On a structure, a non-redundant steel tension member (NSTM) (formerly called a Fracture Critical Member or FCM) is a steel member that experiences tensile stresses from either axial or bending forces. These members are also considered "non-redundant" due to their load carrying functions for the structures. NSTM inspections must be hands on and UAS may only be used for documentation.

5

Priority Action Request (PAR)

After performing the inspections on the distresses, the inspector can then determine whether the distresses are severe enough to notify the Bridge Inspection Team Leaders for Priority Action Request.

6

Pre-Existing Distresses

Upon observing a distress, the inspection team should determine whether the distress existed during the previous inspection, or is new. If the distress is listed in the previous inspection report, and is currently in the same condition and extent as previously recorded, the distress should be noted as such in the new inspection report. If the distress is new, or appears to have increased in severity or extent, the inspector should determine whether the distress should be reported as a PAR.

Figure 3.21: Commentary Boxes to the UAS-Enabled Steel Element Inspection Workflow.

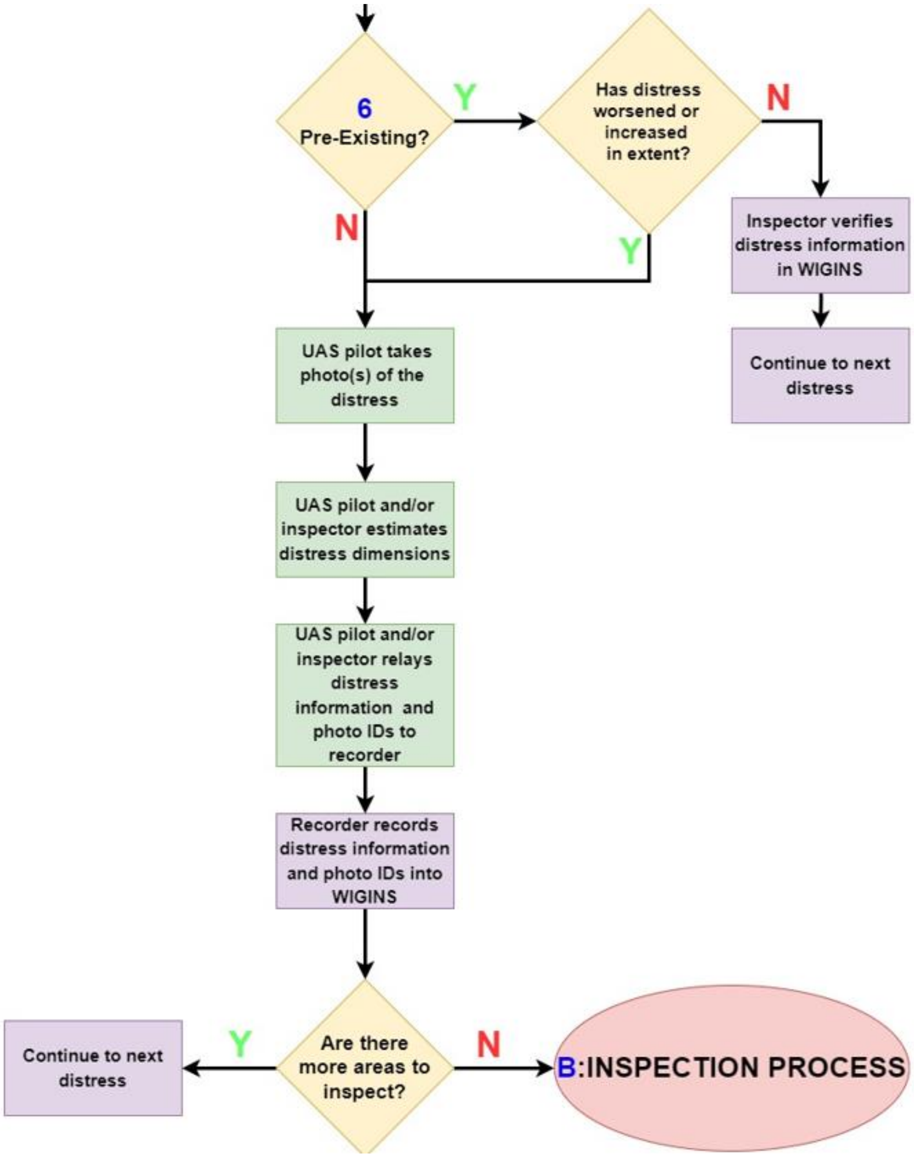


Figure 3.22: UAS-Enabled Steel Element Inspection Workflows with Changes Highlighted in Green. Note that non-redundant steel tension members (NSTM) (formerly fracture critical members) must be inspected hands-on, and the UAS may only be used for documentation. A note was added to Figure 3.19 that is not shown here.

Figures 3.23 and 3.24 present the conventional timber inspection workflow while Figure 3.25 presents the corresponding commentary boxes. Figures 3.26 and 3.27 present UAS-Enabled timber inspection workflow, while Figure 3.28 presents the corresponding commentary boxes. Previous iterations and a deeper discussion on workflow development are provided in Wu (2023). Figure 3.29 presents the differences between the conventional and UAS-enabled versions of the timber workflows.

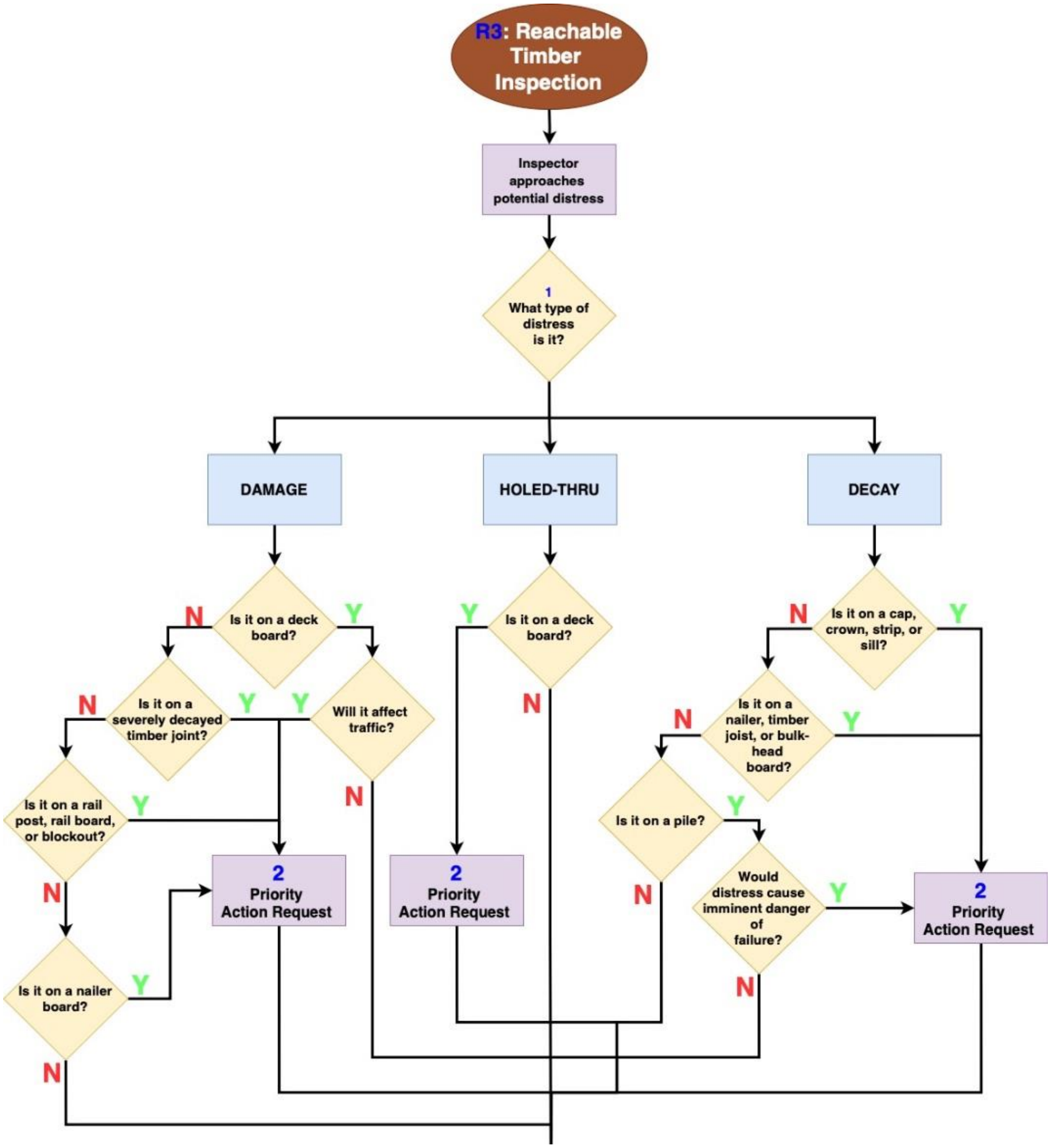


Figure 3.23: Conventional Timber Element Inspection Workflow- Part 1 (upper portion).

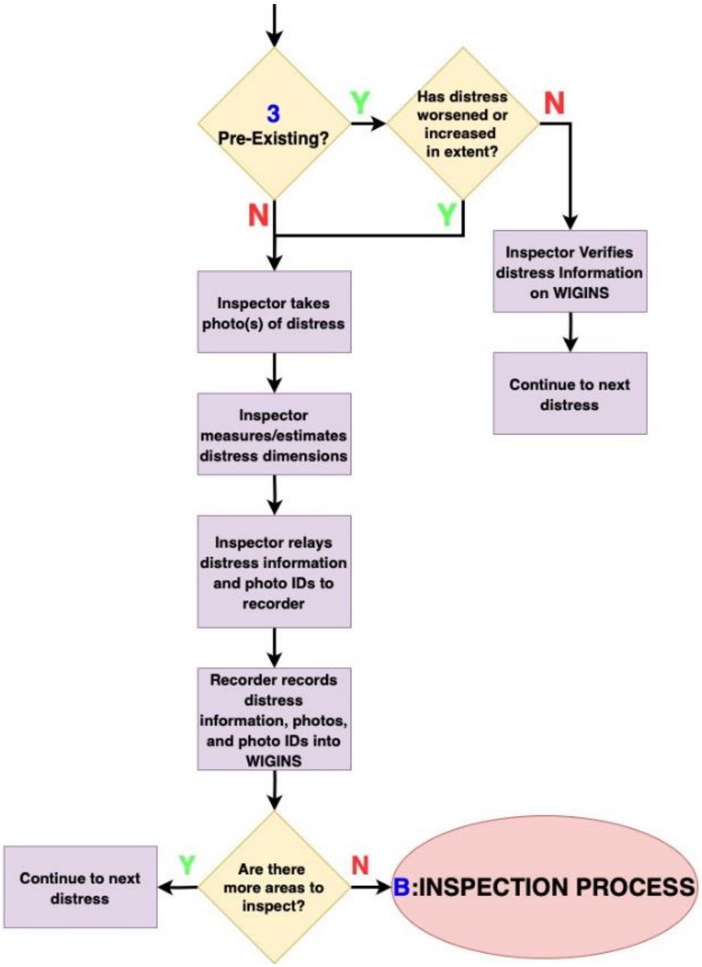
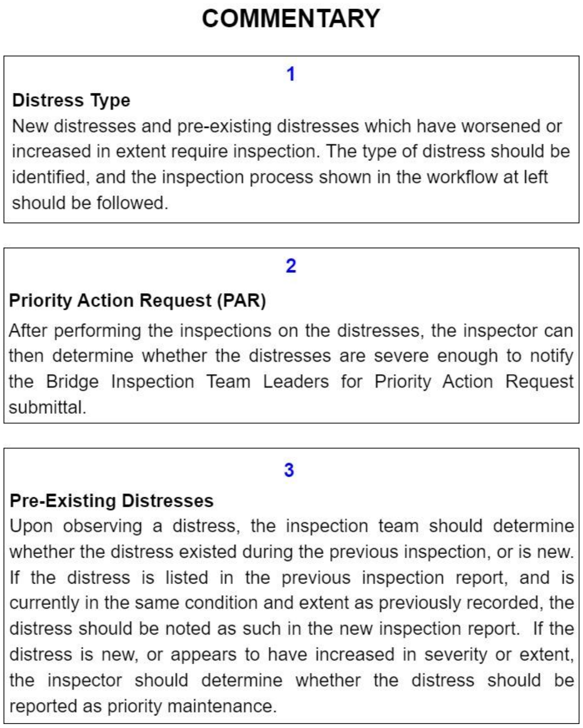


Figure 3.24: Conventional Timber Element Inspection Workflow- Part 2 (lower portion).



COMMENTARY

1

Distress Type

New distresses and pre-existing distresses which have worsened or increased in extent require inspection. The type of distress should be identified, and the inspection process shown in the workflow at left should be followed.

2

Priority Action Request (PAR)

After performing the inspections on the distresses, the inspector can then determine whether the distresses are severe enough to notify the Bridge Inspection Team Leaders for Priority Action Request submittal.

3

Pre-Existing Distresses

Upon observing a distress, the inspection team should determine whether the distress existed during the previous inspection, or is new. If the distress is listed in the previous inspection report, and is currently in the same condition and extent as previously recorded, the distress should be noted as such in the new inspection report. If the distress is new, or appears to have increased in severity or extent, the inspector should determine whether the distress should be reported as priority maintenance.

Figure 3.25: Commentary Boxes to the Conventional Timber Element Inspection Workflow.

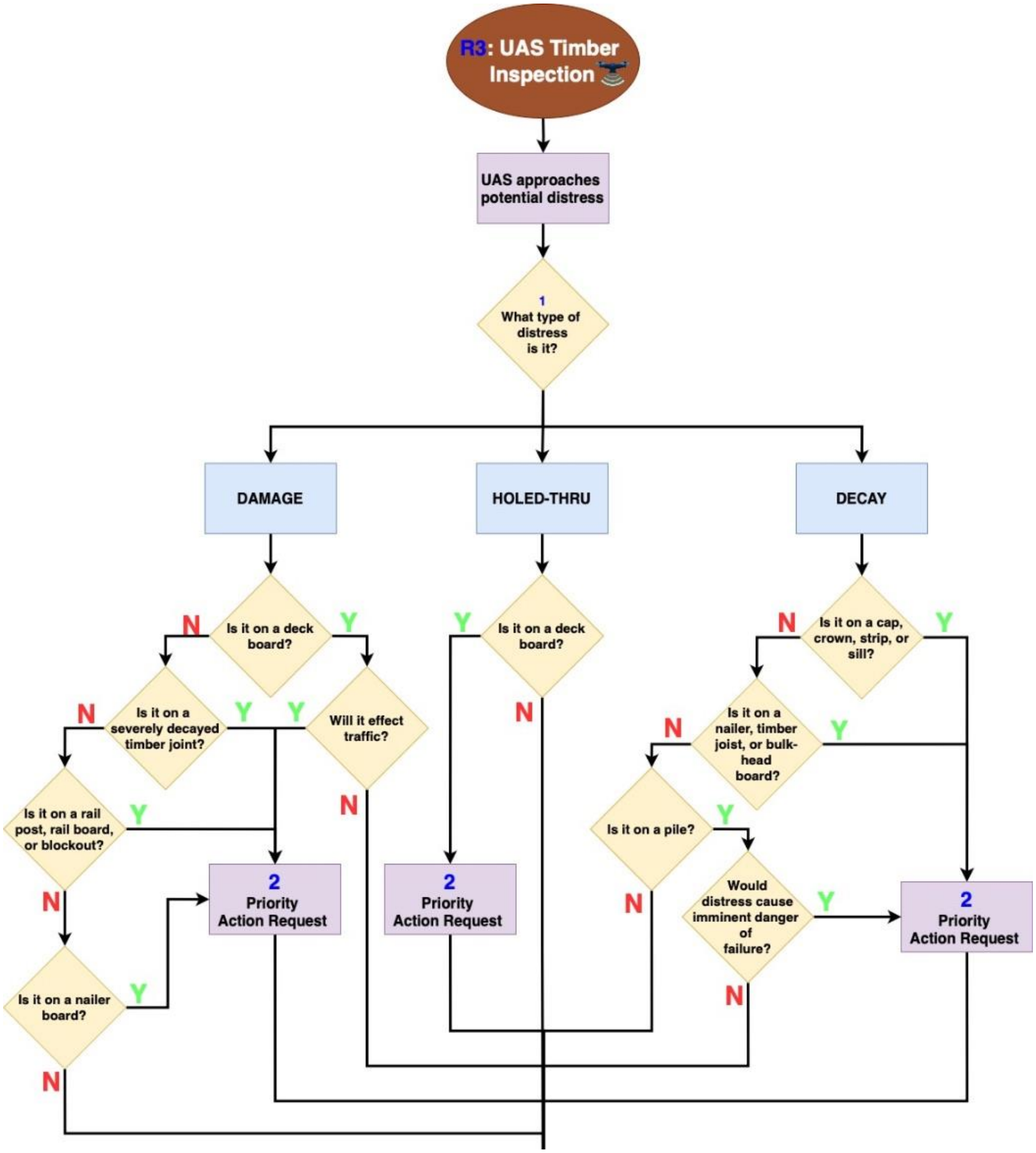


Figure 3.26: UAS-Enabled Timber Element Inspection Workflow- Part 1 (upper portion).

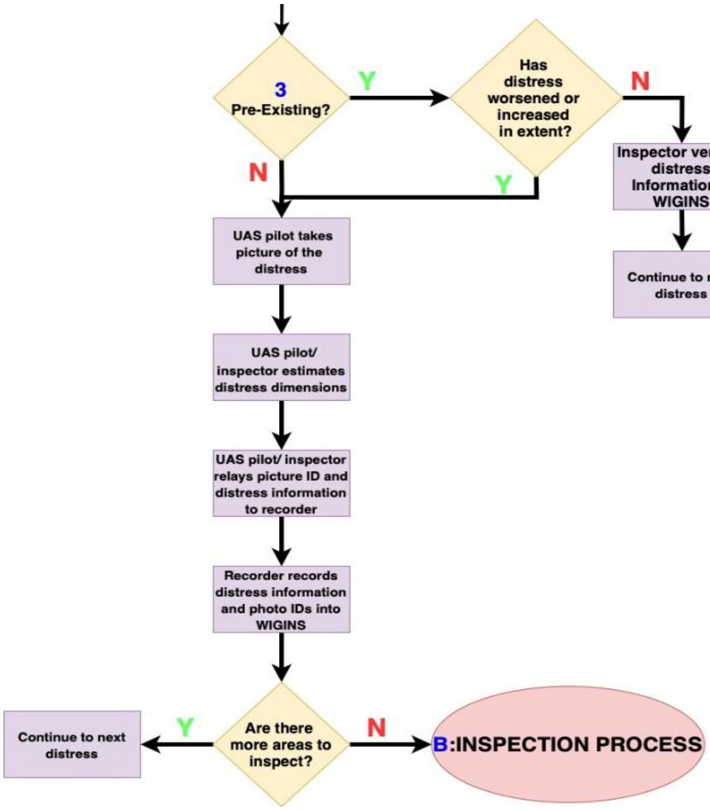
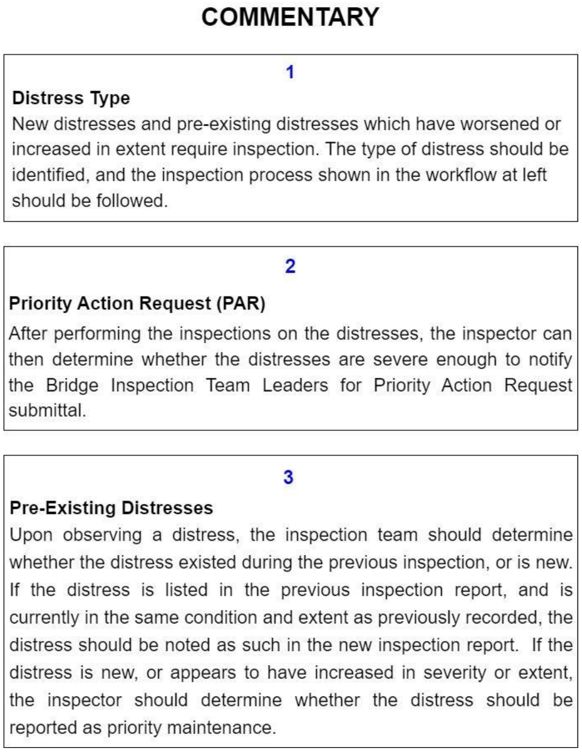


Figure 3.27: UAS-Enabled Timber Element Inspection Workflow- Part 2 (lower portion).



COMMENTARY

1

Distress Type

New distresses and pre-existing distresses which have worsened or increased in extent require inspection. The type of distress should be identified, and the inspection process shown in the workflow at left should be followed.

2

Priority Action Request (PAR)

After performing the inspections on the distresses, the inspector can then determine whether the distresses are severe enough to notify the Bridge Inspection Team Leaders for Priority Action Request submittal.

3

Pre-Existing Distresses

Upon observing a distress, the inspection team should determine whether the distress existed during the previous inspection, or is new. If the distress is listed in the previous inspection report, and is currently in the same condition and extent as previously recorded, the distress should be noted as such in the new inspection report. If the distress is new, or appears to have increased in severity or extent, the inspector should determine whether the distress should be reported as priority maintenance.

Figure 3.28: Commentary Boxes to the UAS-Enabled Timber Element Inspection Workflow.

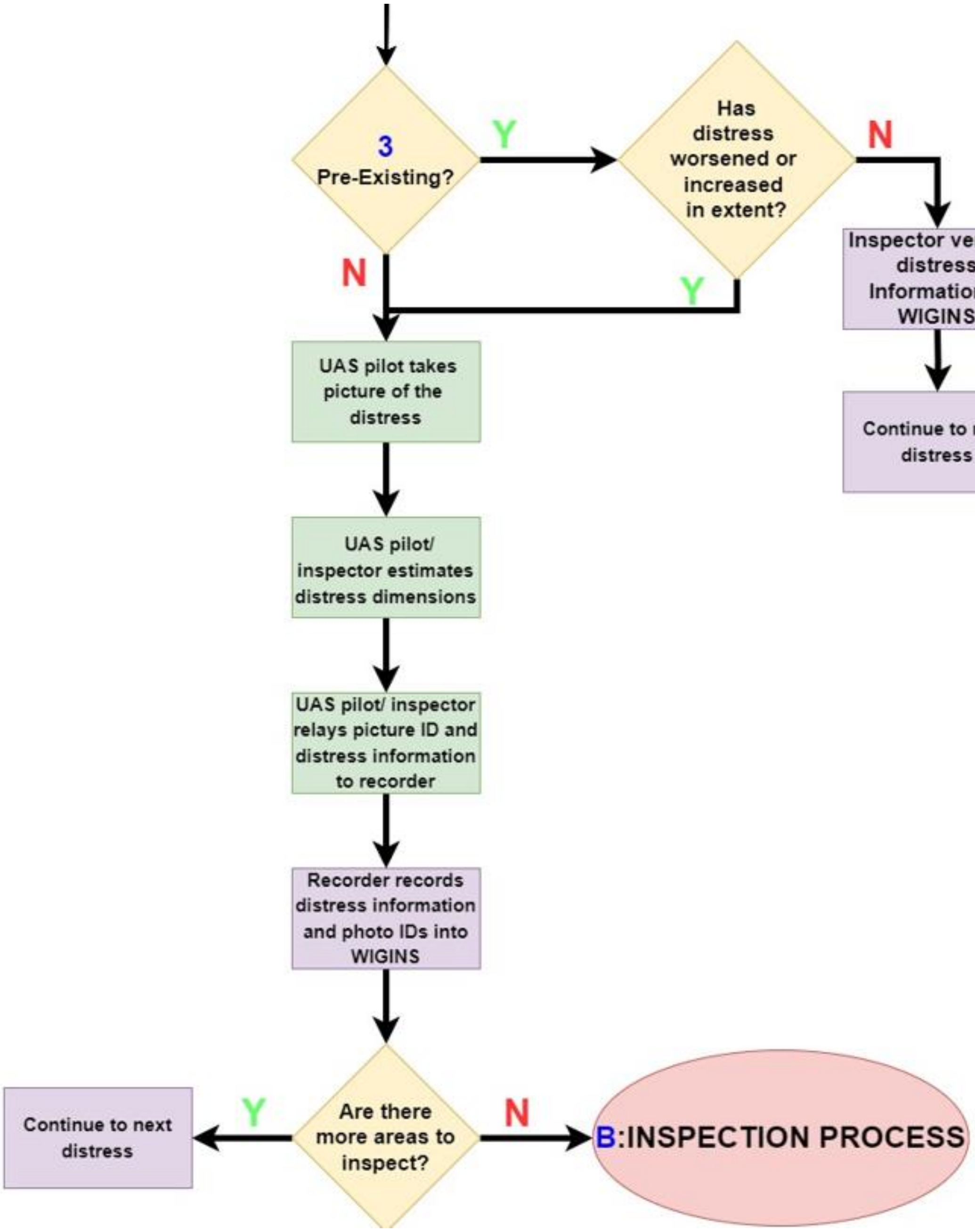


Figure 3.29: UAS-Enabled Timber Element Inspection Workflow (lower portion) With Changes Highlighted in Green.

3.2.4 Required Structure Photos Workflows

UAS should be used to improve the time, safety, and cost efficiency of a bridge inspection operation. While the extent to which a UAS could be helpful to an inspection operation depends on the condition of the bridge, as well as the type of inspection, one specific stage during all inspections in which UASs could be useful is obtaining the required structural photographs. This section introduces the development of the

UAS-Enabled Required Structure Photos Workflow.

Through discussions with the NCDOT Structures Management Unit, it was revealed that even during damage inspection operations and fracture critical inspection operations, UASs could still be deployed to obtain the required photographs due to their excellent mobility around the structures. These photographs include angles of the bridge such as deck approach slabs, guardrails, upstream view, and other features. Some other required photographs could be images of guardrail connections and typical bearings. Oftentimes the angles from which inspectors take photographs are limited by terrain obstacles. The UASs could take photographs from higher and further vantage points, resulting in better views of the bridge. Figure 3.30 depicts an example of a photograph of a profile view of a bridge taken by a UAS. As shown in the figure above, this photograph clearly shows the upstream condition, along with the surrounding environment of the bridge. Although this photograph was taken during a routine inspection, similar photographs would be required in all other inspection operations as well. If a UAS cannot perform this task for a certain bridge inspection, it would be most likely due to the flight restrictions.

Figure 3.30: Profile View of a Bridge Taken By a UAS.

The UAS-Enabled Required Structure Photos Workflow was developed to guide users in obtaining these required photographs. This workflow serves as an extension of the level 2 UAS-Enabled General Bridge Inspection Workflow, where the UAS-Enabled Required Structure Photos Workflow could be seen labeled in a cell. The logic of this workflow is simple, including only guidance on determining the orientation of the structure and obtaining the required photographs, before returning to the level 2 workflow. Figures 3.31 and 3.32 present the UAS-Enabled Required Structure Photos Workflow, and Figure 3.33 presents the commentary box to the workflow.

The development of early iterations of these workflows is described in Wu (2023). The NCDOT SMU provided feedback regarding explicit requirements for photographs taken from four particular angles of the structure. It was conveyed that the approach view, approach guardrail, approach view of opposite face, and approach guardrails of opposite face are angles that could be taken more quickly using a handheld camera. However, it was also acknowledged that these photographs could still be taken with a UAS due to safety considerations that arise due to inspectors walking on and off of the roadway live traffic when obtaining those shots conventionally. To resolve this issue, a comment box was added to allow the users to choose whether a UAS or handheld camera would be used to obtain photographs from these angles.

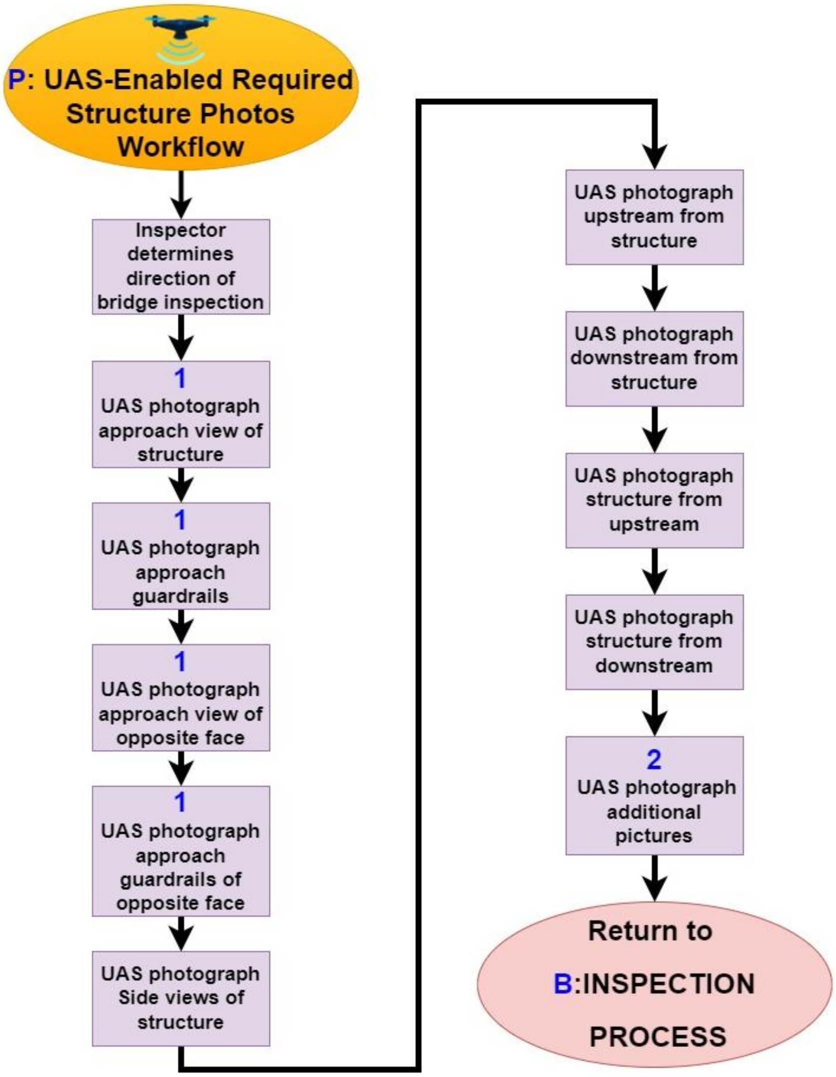
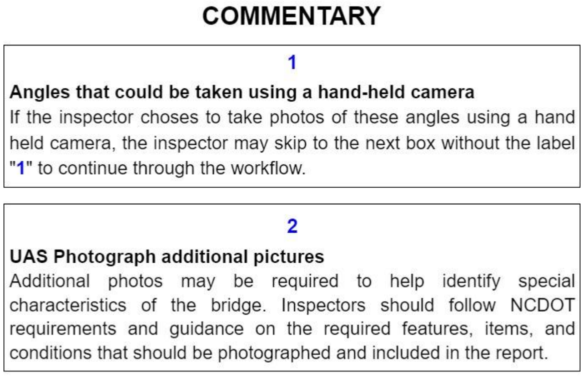


Figure 3.31: UAS-Enabled Required Structure Photos Workflow.



COMMENTARY

1

Angles that could be taken using a hand-held camera

If the inspector choses to take photos of these angles using a hand held camera, the inspector may skip to the next box without the label "**1**" to continue through the workflow.

2

UAS Photograph additional pictures

Additional photos may be required to help identify special characteristics of the bridge. Inspectors should follow NCDOT requirements and guidance on the required features, items, and conditions that should be photographed and included in the report.

Figure 3.322: Commentary Box to the UAS-Enabled Required Structure Photos Workflow.

4 GUIDANCE TO SUPPORT IDENTIFICATION OF CANDIDATE BRIDGES FOR UAS-ENABLED INSPECTION

4.1 Methodology

As described in Chapter 2, the use of UAS to support bridge inspection could reduce safety risks, inspection times, and inspection costs. Although it would be ideal to deploy UASs during the inspection of all bridges, doing so may or may not be economical nor may it be feasible due to specific geographic flight regulations, certain bridge and site features, or other underlying concerns. This chapter details a survey and follow-up analysis that were conducted to identify bridge characteristics and parameters that may affect the suitability of a bridge for UAS-enabled bridge inspection.

The NBI dataset was used to support this work since it provides a database source of detailed information describing the characteristics, locations, and current condition of bridges within North Carolina. The NBI dataset is also individually assembled by all other states and could be used by them if they are interested in performing similar work to evaluate the suitability of their structures for potential UAS-enabled inspection. Due to the large number of bridge characteristics provided within the NBI, a preliminary review and screening of all NBI items (bridge characteristics) pertinent to the suitability of a bridge for UAS-enabled bridge inspection was performed. As a result, a shorter list of bridge characteristics potentially influencing the suitability of a bridge for UAS-enabled inspection was identified. A group of questions was developed in hopes of obtaining input from an expert panel comprised of practitioners with significant experience with UAS-enabled bridge inspections. The expert panel was surveyed using the Delphi Technique in hopes of obtaining consensus. During the survey, the expert panel also identified additional NBI and non-NBI parameters that could influence the suitability of a bridge for UAS-enabled bridge inspection. Some parameters were binary in nature, while others were real-values or categorical. For parameters that were real-values or categorical and sourceable from the NBI, empirical cumulative distribution function (ECDF) plots were created to provide better insight into the approximate percentage of bridges that would be affected by any set limit on the parameter. The following sections detail this process.

4.1.1 Identification of a Preliminary Set of NBI Items

Bridge characteristics, locations, and condition data archived within the NBI provide useful data to support the evaluation of the suitability of a bridge for UAS-enabled inspection. The 2022 NBI ASCII data file for the state of North Carolina was used in this study, as it was the most current data available at the initiation of this effort, using the recording and coding guide as a reference. A set of NBI items potentially influencing the suitability of a bridge for UAS-enabled inspections was identified based on field observations of UAS-enabled bridge inspections, UAS capabilities, and features of the bridges and their surrounding environments. Based on interviews with practitioners and stakeholders as part of this work, the geographic location, geometry, and traffic conditions of a bridge are the three most important factors that influence a bridge's suitability to be inspected with the aid of a UAS. The following is a summary of the takeaways learned from interviews with inspection teams experienced with UAS-enabled bridge inspection:

1) UASs should not operate in FAA flight restriction areas, nor near any aircraft.
2) If a bridge is too small, the setup and inspection time for a UAS-enabled bridge inspection operation may potentially be longer than the setup and inspection time for a conventional bridge inspection operation.
3) Congested environments caused by heavy vegetation and utilities might inhibit UAS flight capabilities.
4) UASs are prohibited from flying over live traffic and pedestrians.
5) UASs may be inoperable in low lighting conditions due to the system requirements of certain UAS models.

Of the 110 NBI items available, 13 were identified as those that could potentially describe the conditions summarized above. The research team was also cognizant that a targeted list of NBI items would also help reduce user fatigue during the survey. The preliminary list of NBI items that were believed to contribute to the suitability of a bridge for UAS-enabled inspection is shown in Table 4.1.

Table 4-1: Preliminary List of NBI Items Identified.

NBI Item	**Item Number**
Latitude	16
Longitude	17
Functional Class	26
Lanes On and Under the Structure	28
Average Daily Traffic	29
Type of Service On	42A
Type of Service Under	42B
Structure Type, Main	43
Number of Spans in Main Unit	45
Structure Length	49
Deck Width, Out to Out	52
Minimum Vertical Clearance Over Bridge Roadway	53
Minimum Vertical Clearance Underclearance	54

It was surmised that the ability of a UAS to operate around a bridge would be dependent to some extent upon conditions that could be inferred from these NBI items. However, to ensure that these assumptions were valid, and to better understand if thresholds existed for some items, a survey was compiled. An expert panel experienced in UAS-enabled bridge inspection was surveyed regarding whether these bridge characteristics or other factors are appropriate for determining the suitability of a bridge for UAS-enabled inspection. These preliminary NBI items would be used to be compiled into a survey, and then given to the expert panel, as described in section 4.1.2. Survey respondents were also asked if there are additional NBI items that should be considered as well.

4.1.2 Delphi Technique to Identify Bridge Characteristics Impacting a Bridge's Suitability for UAS-Enabled Bridge Inspection

Nine industry experts were selected by NCDOT (Mr. David Snoke), based on the candidates' experience with UAS-enabled bridge inspection and/or UAS piloting experience, and their ability to provide insight into which bridge and site characteristics may influence a structure's inspection to be supported by a UAS. Since there is not currently established guidance on how to determine a bridge's suitability for UAS-enabled inspection, the Delphi technique was used to gain consensus amongst the expert panel on what bridge characteristics should ultimately be considered. Out of the nine experts, three work for NCDOT and six are from partnering PEFs. These experts have bridge inspection experience ranging from 5 to 30 years, where most of them have around 20 years of experience. Notably, seven out of the nine experts have extensive experience in piloting UASs to inspect bridges, including the UAS operations lead for the NCDOT. The two other experts did not have piloting experience but were heavily involved in UAS-enabled bridge inspection operations.

A Delphi survey is a method in which convergence can be gained amongst industry experts on certain real-world topics (Hsu and Sandford 2007). The Delphi technique begins with identifying the objective of the survey, in this case, to determine what factors of a bridge could impact the usability of a UAS. After determining the objective, an expert committee is assembled to take part in two rounds of surveys. In the first round of surveys, the participants are asked to complete the survey independently, in this case answering questions relating to the NBI items previously identified in section 4.1.1. The responses from the first-round survey are then organized and provided to the expert panel as they complete a second-round survey. Doing so provides the respondents the opportunity to view the responses of other respondents from the first survey and reconsider their decisions during the second round of surveying. The responses from the second-round survey are then considered to reflect a consensus amongst the expert panel.

4.1.2.1 First Round Survey

Eleven questions were asked during the first-round survey, including questions directed at obtaining the respondents' professional affiliations and their experience with UAS-enabled bridge inspection. The questions were phrased to elucidate information on bridge characteristics, locations, and condition information that may affect the suitability of a bridge for UAS-enabled inspection and that can be described by existing NBI items. This approach allowed respondents to think more generally about the characteristics of a bridge, rather than restricting them to think only about specific NBI items. For example, to understand what the respondents think about Average Daily Traffic NBI item 29 and how it could affect UAS-enabled bridge inspection operations, the survey was phrased "Could you suggest a traffic volume carried on or under a bridge that would prohibit or substantially limit use of UAS during bridge inspection? (e.g., ADT>1000 may be the traffic volume carried that may make a structure a poor candidate for UAS-enabled bridge inspection.)"

Based on the questions developed to obtain the respondents' opinions on the NBI items identified above in Table 4.2, along with additional questions to survey the respondents' background and experience, the survey was compiled and programmed into Qualtrics, a web-based survey development platform, and electronically disseminated to the expert panel. The expert panel of nine individuals were given 10 days to respond.

Table 4-2: First Round Survey Questions.

Page Title	**Comment or Question for the Page**
Introduction	Thank you for participating in this survey. The purpose of this survey is to understand bridge characteristics that bridge inspection experts and UAV pilots think may impact the use of UAVs to support bridge inspection. For certain characteristics, we would also like to know the respondent's thoughts on potential thresholds that could be used to help identify (or sort) the bridge inventory into "suitable for UAV-enabled inspection," "potentially suitable for UAV-enabled inspection" and "not suitable for UAV-enabled inspection."

Location and/or Geographic Features	Please suggest any geographic features that may negatively impact the use of UAVs during bridge inspection. (e.g., UAVs could not support bridge inspection for bridges located in FAA no-flight zones.)
Traffic	Could you suggest a traffic volume carried on or under a bridge that would prohibit or substantially limit the use of a UAV during bridge inspection? (e.g., ADT > 1000 may be the traffic volume carried by a bridge that may make a structure a poor candidate for UAV-enabled bridge inspection.)
Bridge Geometry	Could the length of the bridge or the number of spans impact the usability of UAV during bridge inspection? If so, could you suggest some numerical limits to these attributes? (e.g., if a bridge has >10 spans, a UAV-enabled bridge inspection may be inefficient; a bridge longer than 2 miles and shorter than 50 feet may be inefficient for UAV-enabled bridge inspection.)
Vertical/ Under Clearances	Could the vertical clearance over and under the bridge impact UAV-enabled bridge inspection? If so, what might the numerical threshold be? (e.g., if a bridge has a vertical clearance <10 ft, it may not be suitable for UAV-enabled bridge inspection.)
Deck Width	Could the width of a bridge impact UAV-enabled bridge inspection? If so, what might the numerical threshold be? (e.g., if a bridge is >75 ft wide, UAV-enabled bridge inspection may be inefficient.)
Structure type	Please list any structure type or feature that could potentially inhibit the use of UAV during bridge inspection. (e.g., the truss bridges may be too complex and may not be suitable for UAV-enabled bridge inspection.)
Tell us about yourself	Please tell us a little bit about yourself, what is your experience in UAVs and/ or in bridge inspection?
Closing	Thank you once again for your participation. We appreciate your support of this research project aimed at advancing UAV-enabled bridge inspection.

After the first round of survey results were obtained, the responses for each question were organized. A number of responses to several questions were similar across multiple respondents with only minor differences in phrasing. Therefore, the responses were grouped by similarity and frequency of appearance. For example, for the question "Please suggest any geographic features that may negatively impact the use of UAV during bridge inspection?," four respondents answered with slightly different verbiage that the FAA no-flight zones would inhibit UAS operations. To simplify the analyses for similar responses, the number of respondents replying with a similar answer to each question was denoted. For example, in the example above, results associated with no-flight zones were grouped as "FAA No-Flight Zones (4 respondents)." The question was also relabeled as "Geographical Feature" to best represent what topic was being asked in this question. Similar procedures to identify a question summary item and response grouping were performed for all questions and all responses. Table 4.3 summarizes the results from the first-round survey.

Table 4-3: Summary of the First-Round Survey Responses.

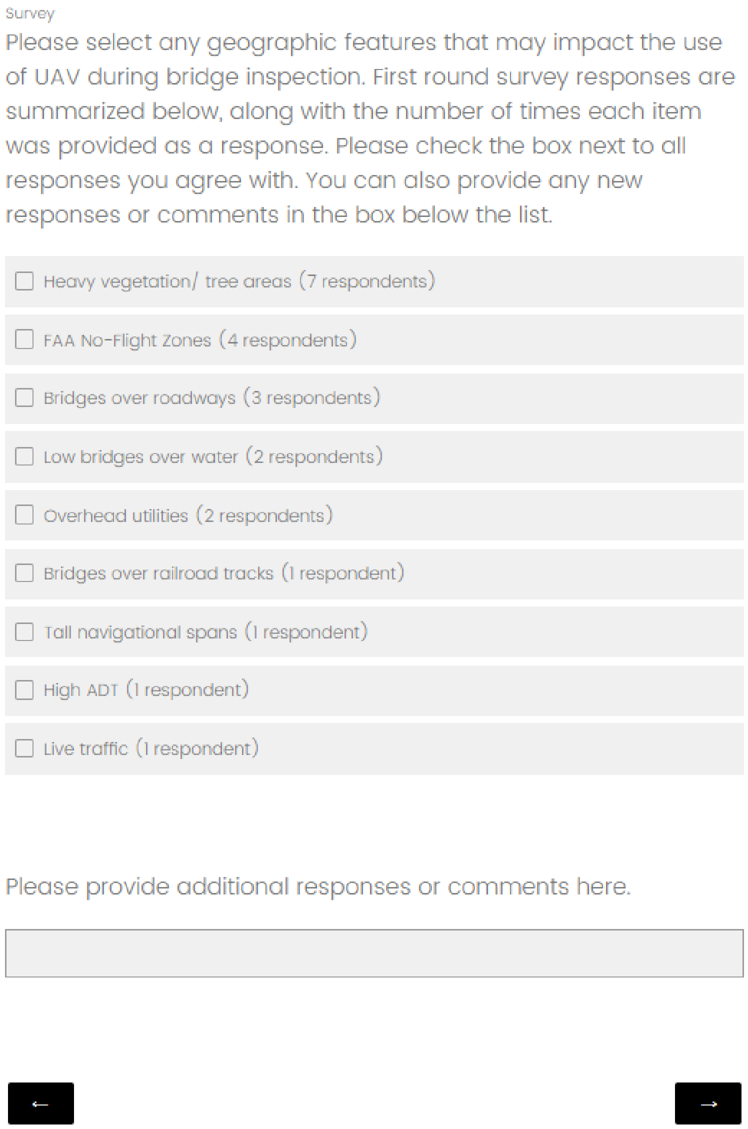
Topic Surveyed	**Responses**	**Number of Respondents**

Geographical Feature	Heavy vegetation/tree areas FAA No-Flight Zones Bridges over roadways Low bridges over water Overhead utilities Bridges over railroad tracks Tall navigational spans High ADT Live traffic	7 respondents 4 respondents 3 respondents 2 respondents 2 respondents 1 respondent 1 respondent 1 respondent 1 respondent
Utility Feature or Others	Power lines/ overhead utilities Utility in structure bays Heavy vegetation Power stations Guywires Radio frequency interference Diaphragms Low freeboard	4 respondents 2 respondents 2 respondents 1 respondent 1 respondent 1 respondent 1 respondent 1 respondent
Traffic Volume	Any amount is fine as long as UAS is not above live traffic Any amount could be a hindrance Depends on pilot Any amount could be fine as long as there is traffic control ADT>2000 ADT>1000 in rural areas	3 respondents 2 respondents 1 respondent 1 respondent 1 respondent 1 respondent
Bridge Length and Number of Spans	Not important as long as pilot can stay close to the UAS Battery life and topography matter most, not bridge length and number of spans Not feasible to inspect bridge during flight, desktop view of images required	9 respondents 2 respondents 1 respondent
Vertical Clearance	Vertical clearance does not matter Depends on UAS Minimum 15 ft under bridge Minimum 30-40 ft Manual flight minimum 8ft under bridge Auto flight minimum 15 ft under bridge Minimum 10 ft clearance to launch Over/under the bridge for >200 ft would be an issue Minimum 6 ft under bridge	4 respondents 2 respondents 1 respondent 1 respondent 1 respondent 1 respondent 1 respondent 1 respondent 1 respondent
Width	No No, but depends on UAS and pilot	5 respondents 4 respondents
Facility Over/ Under	Can't fly over live traffic Railroad authority needs to be contacted Can't fly over pedestrians Can't fly over national security-sensitive facilities Bridges in national parks and over certain reservoirs require special permission	5 respondents 5 respondents 2 respondents 1 respondent 1 respondent
Structure Type	Bridges with tightly grouped elements None Small, low clearance bridges	2 respondents 2 respondents 2 respondents

	Bridge condition <7	1 respondent
Others	Lower condition ratings Poor lighting conditions Strong winds Heavy vegetation	2 respondents 2 respondents 2 respondents 1 respondent
Participant Info	Bridge inspector with UAS-enabled bridge inspection experience Unknown	8 respondents 1 respondent

4.1.2.2 Second Round Survey

A second-round survey was prepared similar to the first round survey with the exception that the responses and frequency of responses for each question from the first round survey were provided to the respondents. This allowed respondents to compare their own responses to the group's responses and make adjustments in their opinion after considering the collective input of their peers. The goal of the Delphi approach is to gain consensus from the panel. By considering the collective input, a respondent may choose to expand his/her initial response to include considerations that he/she may have initially overlooked but do consider important after seeing the opinions of others. Additionally, a respondent may drop a belief or opinion that they initially had if they did not have strong conviction in it and observe that no other respondent shared the opinion in the second-round survey, the respondents were asked to select the first round survey response(s) they agreed with pertaining to each question. The usage of the Delphi Technique was introduced to the respondents at the beginning of the second-round survey. Respondents were also asked to provide additional comments should they have additional input or desire to clarify their responses. Figure 4.1 presents an example of a question asked in the second-round survey. Table 4.3 summarizes the results from the second-round survey. Table A.1 through A.5 in Appendix A provide the raw results extracted from the survey.



Survey

Please select any geographic features that may impact the use of UAV during bridge inspection. First round survey responses are summarized below, along with the number of times each item was provided as a response. Please check the box next to all responses you agree with. You can also provide any new responses or comments in the box below the list.

- ☐ Heavy vegetation/ tree areas (7 respondents)
- ☐ FAA No-Flight Zones (4 respondents)
- ☐ Bridges over roadways (3 respondents)
- ☐ Low bridges over water (2 respondents)
- ☐ Overhead utilities (2 respondents)
- ☐ Bridges over railroad tracks (1 respondent)
- ☐ Tall navigational spans (1 respondent)
- ☐ High ADT (1 respondent)
- ☐ Live traffic (1 respondent)

Please provide additional responses or comments here.

Figure 4.1: Location weather station mounted above the deck.

Table 4-4: Summary of the Second Round Survey Responses.

Topic Surveyed	**Responses**	**Number of Respondents**
Geographical Feature	Heavy vegetation/tree areas Live traffic FAA No-Flight Zones High ADT Overhead utilities Bridges over roadways Low bridges over water	6 respondents 5 respondents 4 respondents 4 respondents 4 respondents 4 respondents 2 respondents
Utility Feature or Others	Power lines/ overhead utilities Heavy vegetation Guywires Radio frequency interference Utility in structure bays Diaphragms Low freeboard Power stations	4 respondents 3 respondents 3 respondents 3 respondents 3 respondents 1 respondent 1 respondent 1 respondent
Traffic Volume	Any amount could be a hindrance Any amount could be fine as long as there is traffic control Any amount is fine as long as UAS is not above live traffic ADT>2000	3 respondents 3 respondents 3 respondents 1 respondent
Bridge Length and Number of Spans	Battery life and topography matter most, not bridge length and number of spans Not important as long as pilot can stay close to the UAS Not feasible to inspect bridge during flight, desktop view of images required	5 respondents 5 respondents 1 respondent
Vertical Clearance	Depends on UAS Auto flight minimum 15 ft under bridge Vertical clearance does not matter Manual flight minimum 8ft under bridge Minimum 10 ft clearance to launch Over/under the bridge for >200 ft would be an issue	3 respondents 2 respondents 2 respondents 1 respondent 1 respondent 1 respondent
Width	No No, but depends on UAS and pilot	6 respondents 1 respondent
Facility Over/ Under	Can't fly over live traffic Can't fly over national security-sensitive facilities Can't fly over pedestrians Bridges in national parks and over certain reservoirs require special permission Railroad authority needs to be contacted	5 respondents 5 respondents 5 respondents 4 respondents 4 respondents
Structure Type	Bridges with tightly grouped elements Small, low clearance bridges Bridge condition <7	4 respondents 3 respondents 2 respondents
Others	Poor lighting conditions	5 respondents

	Lower condition ratings Strong winds Heavy vegetation	4 respondents 4 respondents 4 respondents

By providing the results of each question from the first-round survey to the respondents during the second-round survey, the respondents were able to reinforce and/or expand their result options. Table 4.4 presents a side-by-side comparison of responses and frequencies of the first round and the second-round surveys. It can be seen that the frequencies of most responses changed, therefore also shifting the ranked order of the responses (from highest frequency to lowest frequency of occurrence). It was discovered that some bridge geometrical characteristics that were extracted prior to the distribution of the surveys, such as the number of spans and width, did not receive as much reinforcement of opinion through both rounds of surveys. In other words, the expert panel assisted in eliminating irrelevant bridge characteristics originally proposed by the research group.

It could also be seen that the number of unique responses (responses with only 1 respondent) decreased from 18 to 9 in the second-round survey. This may be due to respondents agreeing with results proposed by others, which they originally did not consider in the first-round survey. The responses that are still unique in the second-round survey could be assumed to be less of a concern for the majority of the expert panel.

Table 4-5: Comparison Between the First-Round and Second-Round Survey Results.

Responses	**1st Round Frequencies**	**2nd Round Frequencies**
Geographical Feature:		
Heavy vegetation/tree areas	7 respondents	6 respondents
Live traffic	1 respondent	5 respondents
FAA No-Flight Zones	4 respondents	4 respondents
High ADT	1 respondent	4 respondents
Overhead utilities	2 respondents	4 respondents
Bridges over roadways	3 respondents	4 respondents
Low bridges over water	2 respondents	2 respondents
Utility Feature or Others:		
Power lines/ overhead utilities	4 respondents	4 respondents
Heavy vegetation	2 respondents	3 respondents
Guywires	1 respondent	3 respondents
Radio frequency interference	1 respondent	3 respondents
Utility in structure bays	2 respondents	3 respondents
Diaphragms	1 respondent	1 respondent
Low freeboard	1 respondent	1 respondent
Power stations	1 respondent	1 respondent
Traffic Volume:		
Any amount could be a hindrance	2 respondents	3 respondents
Any amount could be fine as long as there is traffic control	1 respondent	3 respondents
Any amount is fine as long as UAS is not above live traffic	3 respondents	3 respondents
ADT>2000	1 respondent	1 respondent
Bridge Length and Number of Spans:		
Battery life and topography matter most, not bridge length and number of spans	2 respondents	5 respondents

Not important as long as pilot can stay close to the UAS	9 respondents	5 respondents
Not feasible to inspect bridge during flight, desktop view of images required	1 respondent	1 respondent
Vertical Clearance:		
Depends on UAS	2 respondents	3 respondents
Auto flight minimum 15 ft under bridge	1 respondent	2 respondents
Vertical clearance does not matter	4 respondents	2 respondents
Manual flight minimum 8ft under bridge	1 respondent	1 respondent
Minimum 10 ft clearance to launch	1 respondent	1 respondent
Over/under the bridge for >200 ft would be an issue	1 respondent	1 respondent
Width:		
No	5 respondents	6 respondents
No, but depends on UAS and pilot	4 respondents	1 respondent
Facility Over/ Under:		
Can't fly over live traffic	5 respondents	5 respondents
Can't fly over national security-sensitive facilities	1 respondent	5 respondents
Can't fly over pedestrians	2 respondents	5 respondents
Bridges in national parks, certain reservoirs have required special permission	1 respondent	4 respondents
Railroad authority needs to be contacted	5 respondents	4 respondents
Structure Type:		
Bridges with tightly grouped elements	2 respondents	4 respondents
Small, low clearance bridges	2 respondents	3 respondents
Bridge condition <7	1 respondent	2 respondents
Others:		
Poor lighting conditions	2 respondents	5 respondents
Lower condition ratings	2 respondents	4 respondents
Strong winds	2 respondents	4 respondents
Heavy vegetation	1 respondent	4 respondents

4.2 Use of Survey Results to Evaluate the Potential Candidacy for UAS-Enabled Inspection

The next step of this study was to explore the use of the information obtained from the survey and the impact of potential quantitative or qualitative limits that could be used to designate bridges as good, fair, or poor candidates for UAS-enabled inspection. Some key considerations regarding the bridge characteristics that may influence UAS-enabled inspection are also described in this section. Table 4.6 was created to present all bridge characteristics identified as potentially influencing UAS-enabled inspection through the surveys, along with corresponding NBI item numbers when applicable.

Table 4-6: List of Finalized NBI Items.

Topic	Bridge characteristic	NBI Item
Geographical features	Vegetation (Real-time Event)	N/A
	Live traffic (Binary, Real-time Event)	N/A
	FAA no-flight zone (Binary, use NBI 16&17)	N/A
	Bridges over roadways	28B
	Low bridges over water	54

	National security sensitive facilities (Binary, use NBI 16&17)	N/A
	National parks, reservoirs requiring special permits (Binary, use NBI 16&17)	21
Utility features	Power lines	N/A
	Utilities in structure bay	N/A
	Radio frequency (Binary)	N/A
	Guywires	N/A
	Power stations (Binary, use NBI 16&17)	N/A
	Low freeboard	39
Traffic volume	Traffic control (Real-time Event)	N/A
	ADT	29
	ADT ≥ 2000	29
Bridge geometry	Min 15ft under bridge	54
	Min 8ft under bridge	54
	Min 10ft anywhere to launch	N/A
	Under 200ft	54
Facility over/under	Pedestrian (Binary, Real-time Event)	N/A
	Railroad	21 & 42
Structure type	Tightly grouped elements	N/A
	Small, low clearance bridges	49 & 54
	Bridge condition <7	58, 59, & 60
	Lower condition ratings	58, 59, & 60
Others	Poor lighting conditions (Real-time Event)	N/A
	Strong winds (Real-time Event, use NBI 16&17)	N/A

It was determined that it may be possible to supplement the available NBI data with other sources to assist in the identification of particular bridge characteristics that are not directly indicated in the NBI. For example, to determine if a bridge is within an FAA no-flight zone, near a national security-sensitive facility, or near a power station, the latitudinal and longitudinal coordinates of the bridge (NBI items 16 and 17) could be input into government-published websites to determine UAS usability. Websites such as B4UFLY (FAA 2023) and ArcGIS (Synapse 2023) provide the locations of FAA no-flight zones and the locations of power stations in the U.S. In future work, an algorithm to identify the fraction of bridges falling within the no-fly zones based on latitude and longitude could be developed.

Some of the bridge characteristics identified as potentially problematic for UAS-enabled inspection could be viewed as binary characteristics. Binary classification offers the ability to classify a bridge as unsuitable for UAS-enabled bridge inspection regardless of the other bridge characteristics. For example, if a bridge is located within a FAA no-flight zone, then it can be immediately categorized as unsuitable for UAS-enabled bridge inspection, and therefore other bridge characteristics would become irrelevant for that particular bridge. Other bridge characteristics are based on real-time conditions. These bridge characteristics depend upon real-time information that cannot be found in the NBI, such as live traffic, weather, and poor lighting conditions.

In addition to binary characteristics, many of the bridge characteristics are real values or constrained to a fixed set of integer values that reflect a particular state or condition. The survey was not able to elucidate clear numerical limits to determine the suitability of a bridge for UAS-enabled bridge inspections for the real-value or categorical data items that could be sourced in the NBI. Although some respondents provided numerical limitations for some bridge characteristics, these were limits that were not established through analysis based on the UAS regulations and other mathematical formulations, but only experts' opinions. Furthermore, no clear consensus on specific values was obtained through the survey. To better understand the impact of limits suggested by respondents of these surveys and produce an analysis capable of approximating the percentage of bridges in North Carolina that would be eliminated due to setting a particular limit, a series of empirical cumulative distribution function (ECDF) plots were created, as described in the next section.

4.2.1 Impact of Bridge Characteristic Thresholds on the Fraction of Bridges Suitable for UAS-Enabled Inspection

The Delphi survey results provided several suggested thresholds for certain bridge characteristics that may be useful to NCDOT in determining the suitability of a bridge for UAS-enabled inspection. ECDF models were constructed from the North Carolina NBI data to evaluate the impact of the suggested thresholds on the relative fraction of bridges deemed suitable and unsuitable for UAS-enabled inspection. An empirical cumulative distribution function, or ECDF, plots the observed quantiles on the x-axis versus the calculated cumulative probabilities on the y-axis (Chambers 1983). ECDF plots for the real-value and categorical NBI items were created using the 2022 NBI dataset for only bridges within North Carolina. Eight NBI items shown in Table 4.5 were identified from the survey results, in which their data were extracted to create ECDF plots. The axis limits of some of the plots were maximized (zoomed-in) or otherwise altered to more effectively present the distributions reflected in the plots. The ECDF plots provide insight for developers so that they may understand the relative fraction of bridges that could still be categorized as suitable for UAS-enabled inspections by setting certain quantitative limits. The following descriptions of the ECDF plots aim to illustrate the value of these statistical models:

NBI item 28B- Lanes under the structure: This item describes the number of lanes that pass under a bridge. This item was analyzed resulting from the survey result "geographic feature- bridges over roadways." Since "0" denotes that a bridge does not have any roadway underneath, those structures were taken out of the sample so that only those with lanes underneath could be analyzed. Out of 18,413 structures recorded in the database, only 3,105 structures have lanes underneath. Figure 4.2 shows the ECDF plot of NBI item 28B.

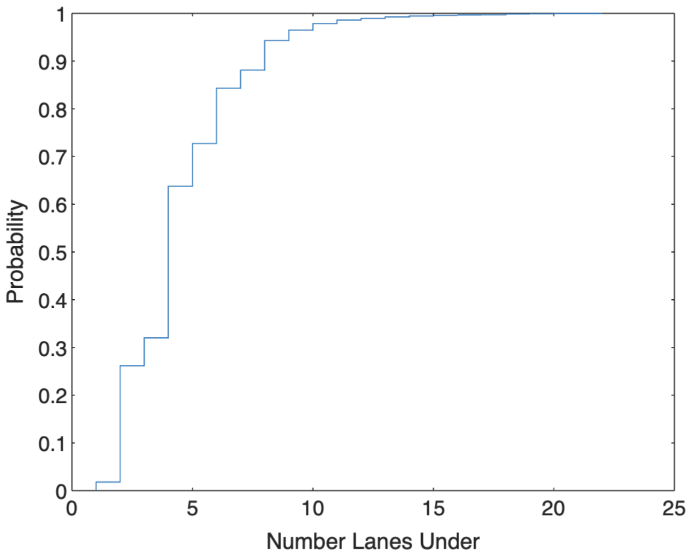


Figure 4.2: Location weather station mounted above the deck.

NBI item 29- Average daily traffic: This item describes the average daily traffic that passes on top of a bridge. This item was analyzed resulting from the survey result "traffic volume- ADT." A numerical limit of 2,000 average daily traffic was suggested by some respondents in the survey. Figure 4.3 shown is the ECDF plot of NBI item 29 with the red dashed line representing an average daily traffic of 2,000. After zooming in to see the region of interest, it could be seen that just over half of the bridges in North Carolina with an average daily traffic of 2,000 or less would be deemed suitable for UAS-enabled bridge inspection. Consequently, the presence of large traffic volumes may be one of the significant obstacles to the use of UAS-enabled inspection. It is also worth noting that since the ADT of a bridge is not a binary characteristic, it would not categorize any bridge as unsuitable for UAS-enabled inspection automatically. For example, for bridges with higher ADTs (set by the experts), UASs could still be utilized to inspect the elements of a bridge that are unaffected by traffic, such as those located on the superstructure. Since the deck carries the traffic, this component could be inspected conventionally during the operation.

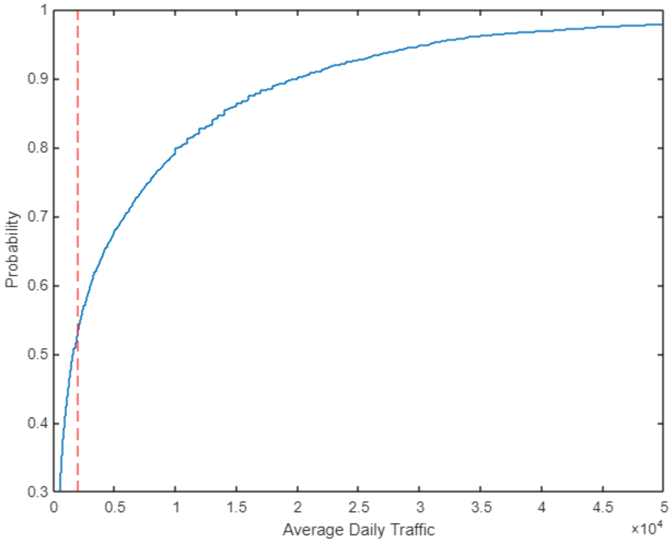


Figure 4.3: Location weather station mounted above the deck.

NBI item 39- Navigation vertical clearance: This item describes the height between the underside of a bridge and the datum specified on a navigation permit. This item was analyzed resulting from the survey result “utility feature- low freeboard.” Out of 18,413 structures recorded in the database, only 73 structures have lanes underneath. It may not be as practical to consider this bridge characteristic when determining the suitability of a bridge for UAS-enabled inspection since only 0.36% of the bridges could be analyzed with regards to this NBI item. Figure 4.4 is the ECDF plot of NBI item 39 zoomed into a region of interest.

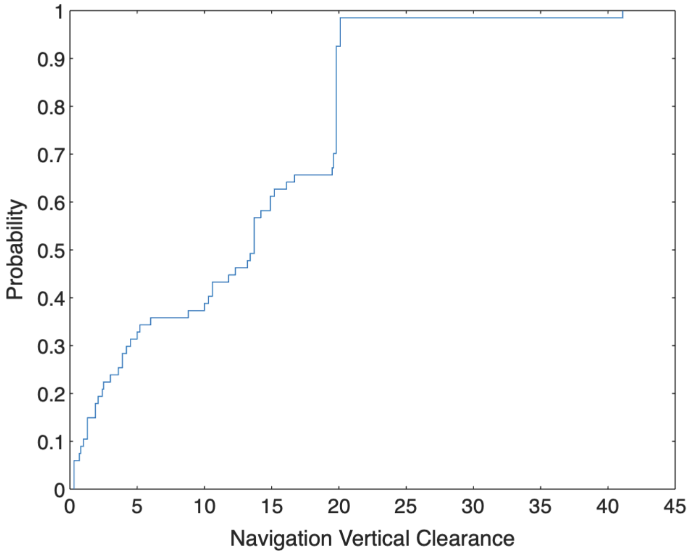


Figure 4.4: ECDF Plot of NBI Item 39- Navigation Vertical Clearance (Y-Axis Limited to Better Convey Distribution).

NBI item 49- Structure length: This item describes the length of a bridge which is the sum of all individual span lengths comprising the structure. This item was analyzed resulting from the survey result “structure type- small, low clearance bridges.” Figure 4.5 is the ECDF plot of NBI item 49 zoomed into a region of interest.

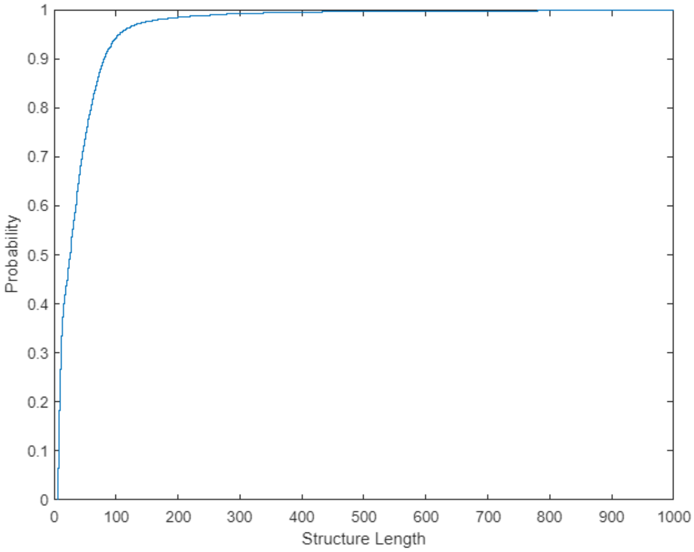


Figure 4.5: ECDF Plot of NBI Item 49- Structure Length Zoomed In.

NBI item 54B- Minimum vertical underclearance: This item describes the minimum vertical clearance over the bridge roadway. Minimum underclearance of 8 ft and 15 ft were suggested by some respondents in the survey. Out of 18,413 structures recorded in the database, 3,729 structures have applicable minimum vertical clearance recorded in the database. Figure 4.6 shows that with a limit of 8 ft (red dashed line) and

15 ft (blue dashed line) or more of minimum vertical underclearance as provided by the survey, approximately 100% and 95% of bridges respectively would be deemed as suitable for UAS-enabled bridge inspection.

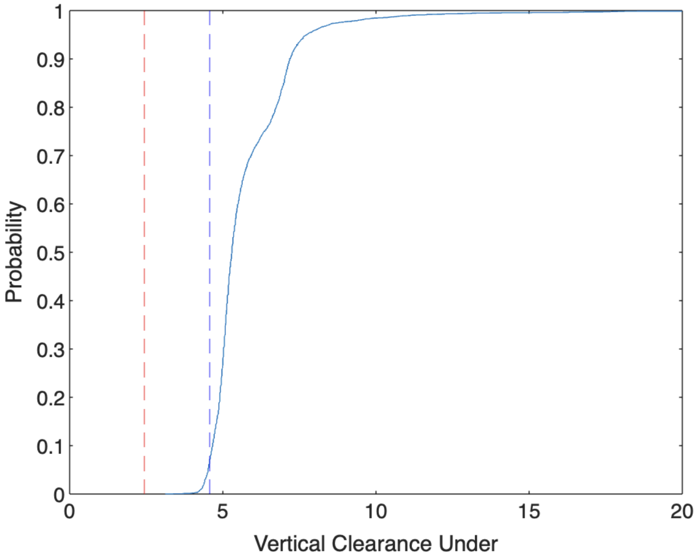


Figure 4.6: ECDF Plot of NBI Item 54B- Minimum Vertical Underclearance (Threshold Drawn for Bridges with At Least 8 Feet and 15 Feet of Vertical Underclearance).

NBI item 58- Deck condition rating: This item describes the condition rating of the bridge deck. A minimum condition rating of 7 was suggested by some respondents for a bridge to be appropriate for UAS-enabled inspection. Figure 4.7 shows that with a minimum deck condition rating of 7 or higher as provided by the survey, only approximately 63% of bridges would be deemed suitable for UAS-enabled bridge inspection.

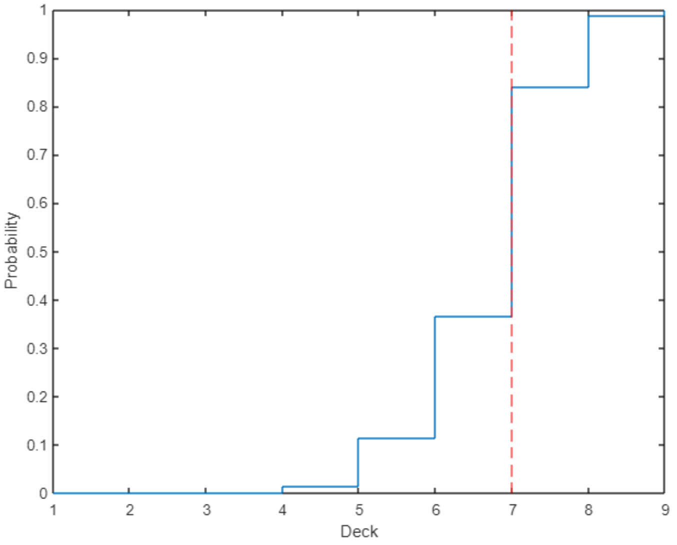


Figure 4.7: ECDF Plot of NBI Item 58- Deck Condition Rating (Threshold Shown for Bridges with a Deck Condition Rating of Less Than 7).

NBI item 59- Superstructure condition rating: This item describes the condition rating of the bridge superstructure. Figure 4.8 shows that with a minimum superstructure condition rating of 7 or higher as provided from the survey, only approximately 60% of bridges would be deemed suitable for UAS-enabled bridge inspection.

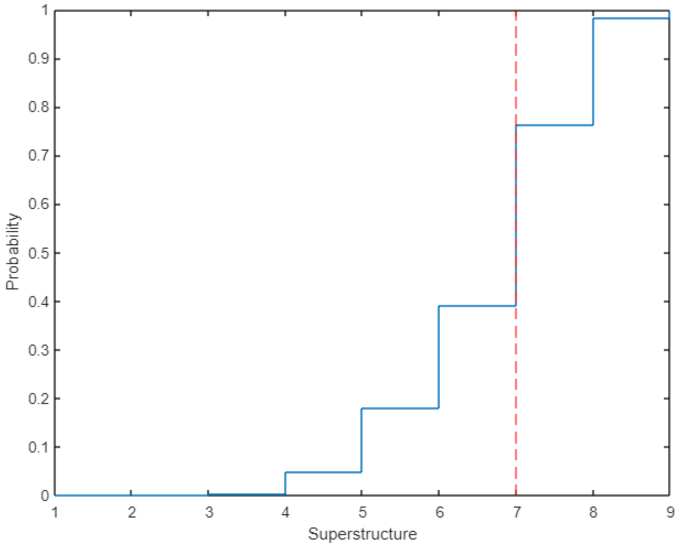


Figure 4.8: ECDF Plot of NBI Item 59- Superstructure Condition Rating (Threshold Shown for Bridges with a Superstructure Condition Rating of Less Than 7).

NBI item 60- Substructure condition rating: This item describes the condition rating of the bridge substructure. Figure 4.9 shows that with a minimum substructure condition rating of 7 or higher as provided by the survey, only approximately 55% of bridges would be deemed suitable for UAS-enabled bridge inspection.

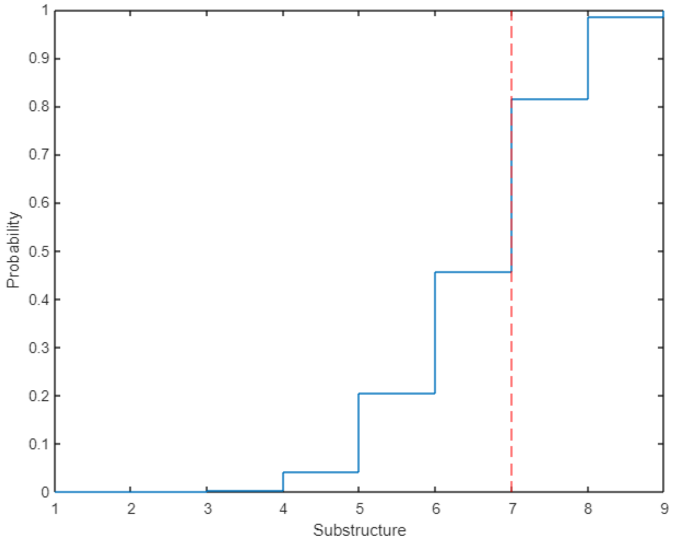


Figure 4.9: ECDF Plot of NBI Item 60- Substructure Condition Rating (Threshold Shown for Bridges with a Substructure Condition Rating of Less Than 7).

Although the condition ratings (deck, superstructure, and substructure) are not considered binary bridge characteristics (where an entire UAS-enabled operation would be unsuitable due to failure to meet one criterion), not meeting the minimum condition rating could possibly entail the inability to inspect that particular bridge component using a UAS. To see the fraction of bridges that have all three components suitable for UAS-enabled inspection (all three components that have at least a condition rating of 7 or above), a separate ECDF plot was created. The lowest condition rating of all bridges was extrapolated to create Figure 4.10. It can be seen that approximately 44% of bridges in the inventory have a minimum rating of 7 for three all bridge components. These would be the bridges that would be suitable for UAS-enabled inspection entirely.

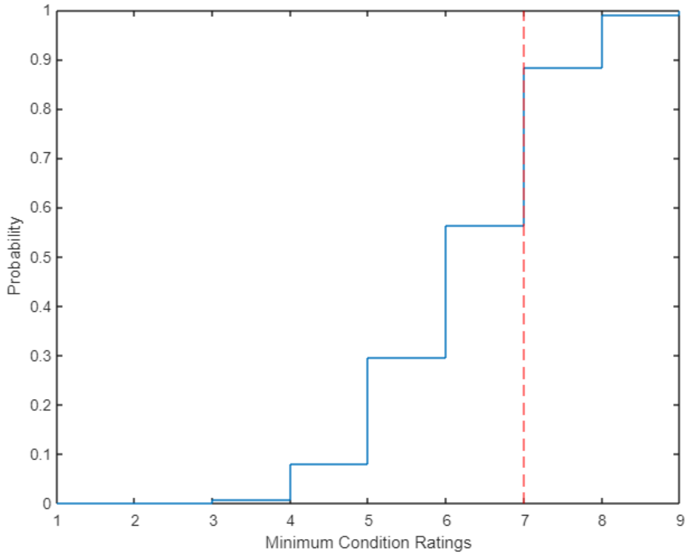


Figure 4.10: ECDF Plot of Minimum Condition Ratings (Deck, Superstructure, and Substructure) for all Bridges in the Inventory.

To further demonstrate how the numerical threshold provided by the survey could be analyzed, the following Venn diagram was created. It can be seen in Figure 4.11 that roughly half of the bridges in North Carolina have an ADT of less than 2000, and about one-third of the bridges have a minimum condition rating of 7. However, only 16% of the total inventory satisfy both criteria. This also provides an additional perspective to users when establishing numerical thresholds for different bridge and site characteristics.

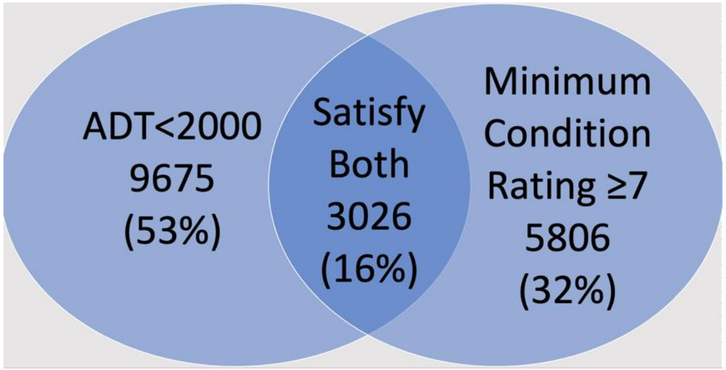


Figure 4.11: Venn Diagram of Structures with a Minimum Condition Rating ≥7 and ADT<2000.

5 IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

After the completion of the field experiments and collecting data, the team focused on post-processing, analysis, reporting, and storing of data from UAV-assisted bridge inspection. The post-processing of data from UAV-assisted bridge inspection is essential to extract meaningful information from the collected data. The data processing techniques may include image and video processing, point cloud processing, and feature extraction. These techniques can help to remove noise, filter out irrelevant data, enhance the quality of the data, and extract useful information (Ben-Shabat et al. 2017, Guo et al. 2020). The processed data can then be analyzed and interpreted to provide valuable insights into the structural and visual condition of the bridge components, which can help bridge owners and engineers make informed decisions about the maintenance and repair of bridges.

Therefore, the raw collected data will be processed, analyzed, and interpreted accordingly. The analyzed data must be interpreted to provide meaningful information to the bridge owners and engineers. The interpretation may include the identification of the severity of the distresses and the recommendation of repair and maintenance strategies. Figure 5.1 illustrates the workflow that governs the respective sequence of operations under this phase.

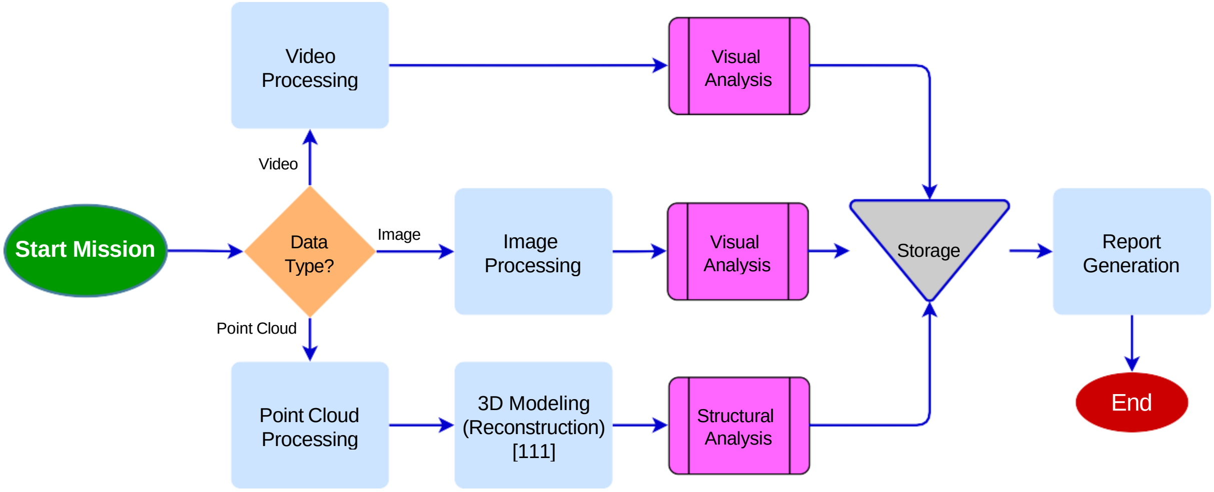


Figure 5.1: Proposed Workflow for the Post-Inspection Phase of the Methodology.

- Data Processing: The collected data from UAV-assisted bridge inspection is often affected by various factors such as motion blur, shadows, occlusions, reflections, noise, and other artifacts that can degrade the quality of the data. Therefore, before the data can be analyzed and interpreted, it must undergo a series of processing steps to remove the artifacts, enhance the quality of the data, and extract useful information. Key data types collected in UAV-assisted bridge inspection are images, videos, and point clouds of the bridge. These visual data provide important information about the condition of the bridge, such as the presence of cracks, corrosion, or other signs of damage. However, raw images, videos, and point clouds are often difficult to analyze manually, especially in large datasets. Therefore, image and video processing techniques are often employed to extract meaningful information from visual data.
- Image and Video Processing: The images and videos captured by the UAVs are processed using various techniques to enhance the visual quality and extract relevant information.
- Data Analytics: The processed data from the previous stage should be analyzed to identify the structural and visual condition of the bridge components. The analysis can help bridge owners and engineers make informed decisions about the maintenance and repair of bridges. The analysis may

include the identification of deformations, displacements, and other structural distresses. The data analysis techniques may include machine learning, computer vision, and artificial intelligence. The structural condition of the components may be assessed based on the point clouds captured by the UAV. In this section, we will discuss the different data analysis techniques used in UAV-assisted bridge inspection.

- Visual Analysis: The visual condition of the components may be assessed based on the images and videos captured by the UAV. The analysis may include the identification of distresses and other structural abnormalities. Potentially, data analysis techniques such as machine learning, computer vision, and artificial intelligence could be used to replace or supplement the current practice of manual readings.
- Machine learning algorithms can be used to automatically analyze large amounts of data, such as images or point clouds, and identify patterns or anomalies that may indicate structural deficiencies or defects in the bridge. By training a machine learning algorithm on a large dataset of images or point clouds of bridges with and without cracks, the algorithm can learn to identify the visual patterns associated with cracks and accurately detect them in new images or point clouds. Furthermore, by training a machine learning algorithm on a large dataset of images or point clouds of bridges with different types and degrees of damage, the algorithm can learn to identify and classify the condition of different bridge components, such as girders, piers, or abutments. This can significantly reduce the time and effort required during the post-inspection phase and can help inspectors to quickly assess the overall condition of the bridge and prioritize maintenance or repair efforts.

6 RESEAECRH PRODUCTS

Research Product 1	Workflows for conventional and UAS-Enabled Bridge Inspection
Suggested User	NCDOT Division of Aviation and Structures Management Unit
Recommended Use	Workflows could be integrated into the SMU Inspection Manual, training materials, or other technology transfer and components
Recommended Training	These workflows directly support training of inspectors and pilots from NCDOT and PEF.

Research Product 2	Guidance to support identification of candidate bridges for UAS-enabled inspection
Suggested User	NCDOT Structures Management Unit
Recommended Use	Insight and thresholds provided by expert panel in survey can be used to guide development and implementation of policies and procedures associated with UAS use in structure inspection, data collection, and reporting.
Recommended Training	None at this time.

Research Product 3	A Time Estimation Tool for Logistic Planning for UAV-Assisted Bridge Inspection (provided in Appendix C)
Suggested User	NCDOT Structures Management Unit and NCDOT Division of Aviation
Recommended Use	The tool can be used as a pre-inspection step to assess the required amount of time and number of batteries (flight times). See Appendix C for details.
Recommended Training	None at this time.

7 CONCLUSION

The objective of this research was to provide the NCDOT with tools to advance the implementation of UASs to support its bridge inspection practices. This research included the development of a series of workflows to guide inspection personnel when conducting UAS-enabled bridge inspections, and the identification of bridge and site characteristics that should be considered when determining the suitability of a bridge for UAS-enabled bridge inspection.

A literature review was performed to better understand current bridge inspection requirements, current progress of UAS-enabled bridge inspection technologies, and current workflows developed to support UAS-enabled bridge inspection. A review of published literature revealed that the level of detail provided by the currently available workflows was not sufficient to support inspection teams integrating UAS operations into NCDOT bridge inspection procedures. An extensive series of field observations of bridge inspections of a range of structures, performed by different NCDOT and PEF inspection teams, was used to develop an understanding of practical aspects of bridge inspection that would otherwise not be required through descriptions available in the published federal or NCDOT inspection requirements. Operations and decisions made by the inspection personnel were found to vary amongst different inspection teams based on preferences, risk tolerances, site/structure conditions, available resources, and other factors. After gaining an understanding of the considerations influencing bridge inspection processes, a series of workflows generally describing the Routine inspection of typical bridges was developed, along with guidance tailored to support field inspection personnel in both conventional and UAS-enabled inspections.

A three-level workflow system was developed based on the consideration of current inspection requirements, current UAS technological capabilities, and observed inspection personnel behaviors. Conventional inspection workflows were first developed for each workflow level to describe the overall logic of a typical (non-UAS-enabled) bridge inspection approach. These conventional workflows were then used as a basis for amendments to integrate UAS operations and capabilities, resulting in a series of UAS-enabled inspection workflows. The workflows developed are as follows:

- Level 1: Conventional/ UAS-Enabled Overall Inspection Framework Workflows
- Level 2: Conventional/ UAS-Enabled General Bridge Inspection Workflows
- Level 3: Conventional/ UAS-Enabled Concrete Element Inspection Workflows
- Level 3: Conventional/ UAS-Enabled Steel Element Inspection Workflows
- Level 3: Conventional/ UAS-Enabled Timber Element Inspection Workflows
- Level 3: UAS-Enabled Required Structure Photos Workflow

This research also identified bridge characteristics and site features that could affect the suitability of a bridge for UAS-enabled bridge inspection. These bridge characteristics were identified through a series of Delphi surveys, where an expert panel with UAS-enabled bridge inspection experience was directed to provide a consensus of opinion on the bridge and site characteristics influencing the ability to use a UAS to support inspection. As a result, 28 bridge characteristics were identified as impactful toward a bridge's suitability for UAS-enabled inspection. Some of the bridge and site characteristics that were mentioned the most were heavy vegetation, live traffic, national sensitive facilities, and poor lighting conditions. For real-value and categorical bridge characteristics that could be found in the NBI, ECDF plots were created to show how setting particular numerical thresholds proposed by the expert panel would fractionate the bridge inventory into those where a UAS could be used to enhance the inspection or may not be used. Future thresholds for different characteristics could be identified by NCDOT, who would likely desire to consider both the optimization of UAS utility as well as ensure that the threshold does not inadvertently preclude (or include) an excessive quantity of bridges in North Carolina. Through the ECDF analysis, it was discovered that an ADT of 2,000 limit as suggested by the expert panel could label up to almost half of the bridges in North Carolina as unsuitable for UAS-enabled bridge inspection.

7.1 Future Research Needs

Since the advancement of UAS technologies is still in progress, the developed workflows should consider the future technological capabilities of the UASs. All of the current action items as described in the workflows are based on UAS serving only as mobile cameras. However, new UAS technologies such as hyperspectral imaging, ground penetrating rating, and higher accuracy LiDAR technologies may impact the decision trees of the current workflows. Artificial intelligence models used to identify and evaluate distresses could also be used to reduce the workload of inspection personnel as well as speed up inspection time. New bridge inspection regulations on the federal and state levels may potentially appear to support UAS-enabled operations.

The next steps towards integrating UAS into the inspection process should include efforts to validate the quality of the inspection data captured from UAS operations, ensuring that the inspection data obtained via UAS videos/photos are at least equally as good, if not better than those that can be obtained through conventional means. A controlled experimental program, where inspection data such as distress measurements (inspector estimating the size of a distress through the UAS video feed) and severity are obtained conventionally and via a UAS should be performed. Conventional vs. UAS-enabled inspection of the same bridge could be performed using different sets of inspectors, UAS pilots, and different UAS equipment. The results could be compared, providing insight into the reliability of UAS-obtained data and the variability that could be associated with operators, equipment, and other external factors. Having multiple sets of inspectors and pilots inspecting the same bridge may help improve the experiment.

Additional cost analysis between conventional and UAS-enabled inspection operations could be performed to inform stakeholders of the benefits that can be achieved by the implementation of UASs into current bridge inspection practices. Hard costs such as capital investment, personnel training, and other UAS-related fees should be considered, and compared to the cost reductions associated with inspection personnel work time and traffic control/ safety support time. Soft costs such as the improvement of work zone safety and the reduction of traffic delays should also be analyzed.

Another recommended task for future research is the development of an algorithm to classify bridges based on their suitability for UAS-enabled bridge inspection. This may help identify the number of bridges in North Carolina that are suitable for UAS-enabled bridge inspection and could provide stakeholders with justification to advance UAS utilization within the state (in addition to the other benefits described in Chapter 2). The data contained within the NBI could be useful for constructing the algorithm, especially the NBI items that were identified in Chapter 4 of this thesis. However, as discussed previously, there are some bridge characteristics pertinent to UAS-enabled bridge inspection that cannot currently be found in the NBI. It is recommended to explore the possibility of adding those bridge characteristics into the NCDOT BMS or linking other external sources to WIGINS Element, to aid the development and implementation of the algorithm.

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APPENDICES

FOR
FINAL REPORT

North Carolina Department of Transportation
Research Project No. 2022-10

Developing Workflow, Implementation Tools, and Guidance for Efficient UAV-enabled Bridge Inspection

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A.1 APPENDIX A: FIRST-ROUND SURVEY RESULTS (supporting material for Chapter 4)

Table A-1: First-Round Survey Results Part 1

Q0	**Q1**
Please provide your name, affiliation, and email.	**Please suggest any geographic features that may negatively impact the use of UAV during bridge inspection. (e.g., UAVs could not support bridge inspection for bridges located in FAA no-flight zones.)**
Respondent 1	Any structure located in a "Restricted Airspace" zone, structures in MTR's (military training routes).
Respondent 2	Heavy/dense vegetation. Routes with high AADT volumes - carried and/or intersected by structure. Maybe or maybe not a "geographical feature", but we have noticed frequent signal loss with structures in rural areas that require flying beyond visual line of sight.
Respondent 3	Bridges in MOA's, Bridge's in densely vegetative areas.
Respondent 4	Powerlines or overhead utilities that might interfere, heavy vegetation under the bridges, high wind speeds i.e., along the coast.
Respondent 5	Trees adjacent and or under the bridge.
Respondent 6	Dense vegetation under or on the sides of the bridge. Low bridges over long stretches of open water. (This issue can be remedied by using a boat to launch from).
Respondent 7	Bridges over roadways (probably an obvious response); bridges that require taking off and landing from a boat (not impossible but a difficult task with limited opportunities for on-the-job training and experience); bridges surrounded by excessive vegetation growth or power lines in close proximity.
Respondent 8	Structures in No-fly zones, over Railroad tracks, with very tall navigational spans.
Respondent 9	Vegetation, outcroppings, Restricted airspace, overhead utilities, live traffic.

Table A-2: First-Round Survey Results Part 2

Q0	**Q2**
Please provide your name, affiliation, and email.	**Please suggest any utility feature or other appurtenances that may negatively impact the use of UAV during bridge inspection. (e.g., power lines adjacent to or near the structure may interfere with flight path, nearby pedestrian walkways may impede visibility, etc.)**
Respondent 1	heavy vegetation at or very near the structure is the most common issue we have noted while using UAV's during bridge inspections.
Respondent 2	Utilities are sometimes present in structure bays and/or along outside faces of exterior beams/girders.
Respondent 3	Tall trees, power stations near area, cross running railroad tracks.
Respondent 4	
Respondent 5	if performing a low altitude flight of the deck power and phone lines may limit how tight we can get to the deck.
Respondent 6	Low-clearance bridges over a road with active traffic require a skilled pilot and an attentive visual observer.
Respondent 7	Cell or radio towers, guywires, poles, radio frequency interference.
Respondent 8	power lines, signs attached to bridge, diaphragms, utility raceways attached to underside of deck, low freeboard under the bridge which triggers the proximity sensors of the UAV.
Respondent 9	Overhead Utilities.

Table A-3: First-Round Survey Results Part 3

Q0	**Q3**
Please provide your name, affiliation, and email.	**Could you suggest a traffic volume carried on or under a bridge that would prohibit or substantially limit use of a UAV during bridge inspection? (e.g., ADT > 1000 may be the traffic volume carried that may make a structure a poor candidate for UAV-enabled bridge inspection.)**
Respondent 1	Any traffic volume active under a bridge would prohibit the use of a UAV as flights over traffic are not permitted.
Respondent 2	Traffic under a structure would be the main concern, and ADT wouldn't really be much of a factor, because any amount of traffic would be a hindrance.
Respondent 3	not sure about that one.
Respondent 4	Interstate traffic speeds, traffic lanes needing lane closures in order to access.
Respondent 5	I have completed top deck inspection on 3 lane highways with an adt above 20,000. We needed to perform 3 separate flights and then deleted many photos with multiple cars in the photo. We then stitched the photos and used FIPAS to perform an automated crack detection on the deck.
Respondent 6	The bridge can have any amount of traffic volume while the underside is being inspected. When inspecting the top/bridge deck, less traffic is typically better. (ADT>2000). However, we have UAVs with high quality zoom lenses that can be far away from the subject and traffic, while still collecting the data required.
Respondent 7	HDR pilots are not allowed to fly over any traffic, but low volumes of traffic could allow flights over / under the bridge during breaks in traffic. I would guess an ADT less than 1000 in rural areas might be acceptable, but it would have to be approved internally on a case-by-case basis.
Respondent 8	We do not use UAVs on bridges which have active traffic (including railroads, unless we have flaggers) under it. For bridges carrying traffic over a water body, traffic volume is not a concern.
Respondent 9	We typically do not fly over live traffic and the majority of information can be gathered from an offset flight not over traffic.

Table A-4: First-Round Survey Results Part 4

Q0	**Q4**
Please provide your name, affiliation, and email.	**Would the length of the bridge or number of spans impact the usability of UAV during bridge inspection? If so, what are some numerical limits to these attributes? (e.g., if a bridge has >10 spans, a UAV-enabled bridge inspection may be inefficient; a bridge longer than 2 miles and shorter than 50 feet may be inefficient for UAV enabled bridge inspection.)**
Respondent 1	Length would not necessarily affect the use of a UAV as long as it is possible to walk the spans as flight progresses through the structure
Respondent 2	Length should not be a factor in determining usability. For "long" structures, the pilot could work from a boat, or roadway shoulder on top of the structure (shoulder width permitting). If flying BVLOS, I would not recommend anything larger ~150ft due to signal loss/interference. For "Short" structures, again, length is irrelevant. Structure height would be a better determining factor. Any structure with at least two spans and a height of ~40' or greater could be a potential candidate.
Respondent 3	Depends on location and mode of travel. Boat following UAV or could use gator to follow drone.
Respondent 4	Not necessarily. If bridge is longer than 10 spans or say few hundred feet, the pilot might need to be in a boat in order to keep UAV within range of the controller.
Respondent 5	It is not feasible to inspect the bridge during the flight. The photos need to be organized and a desktop inspection needs to be completed. So, I would say no limit based on size as long as the photos are well organized.
Respondent 6	The major issue would be connection issues. If the drone pilot is too far from the UAV, the connection and video feed to the remote controller may be compromised. The number of spans is irrelevant as long as the pilot is close enough to maintain solid connection to the drone. (e.g., a low bridge stretching for 2-3,000 feet or more over open water can present an issue. This issue can be remedied by launching and landing from a boat).

Table A-5: First-Round Survey Results Part 5

Q0	**Q5**
Please provide your name, affiliation, and email.	**Would the length of the bridge or number of spans impact the usability of UAV during bridge inspection? If so, what are some numerical limits to these attributes? (e.g., if a bridge has >10 spans, a UAV-enabled bridge inspection may be inefficient; a bridge longer than 2 miles and shorter than 50 feet may be inefficient for UAV enabled bridge inspection.)**
Respondent 7	Immediate considerations for me are battery life and the topography beneath the bridge (for landing and launching purposes). The battery life for the drone I use, Skydio 2+, provides roughly 25 minutes of flight time per battery. For a bridge in good condition and 4 to 6 beams, the battery life would allow for an inspection of roughly one span, and both faces of a bent. My approach is to fly one side of the bent inspecting the beam ends, bearings, cap and columns (or piles), repeat on the other side of the bent, and then fly along the span inspecting the deck / beams. If battery life allows, I will fly along the near face of the next bent, but I normally can't complete the entire bent (again, depending on the number of defects we are trying to see and capture). With that approach, a good candidate is a five to seven-span bridge with good launch and landing locations beneath the bridge and access that allows line-of-sight of the drone. With bridges that require more battery life, the best approach is to have access to the truck for charging the batteries and rotating the batteries during the inspection. The truck has to be on to charge the batteries, so it needs to be accessible. I haven't had a need to use more than 7 flights (battery lives) during an inspection yet, but we did not have access to the truck to charge the batteries, so we left the bridge site to charge and returned later in the day. These approaches are different if we are only flying along the side of the structure and capturing what we can without going beneath the deck. The distance for those flights would then be controlled by battery life and line-of-sight of the drone.
Respondent 8	Depends on UAV capability; over 200 feet length usually requires pilot to reposition.
Respondent 9	Yes. The crew must maintain visual contact with the drone. A longer bridge could be inspected by drone by taking off and landing on boats or emergency pull off areas on the deck. A bridge small enough to inspect with a ladder would be inefficient to inspect by drone.

Table A-6: First-Round Survey Results Part 6

Q0	**Q6**
Please provide your name, affiliation, and email.	**Could the vertical clearance over and under the bridge impact UAV enabled bridge inspection? If so, what might the numerical threshold be? (e.g., if a bridge has a vertical clearance <10 ft, it may not be suitable for UAV-enabled bridge inspection.)**
Respondent 1	Vertical clearance (or lack thereof) would not hinder the use of a UAV.
Respondent 2	Vertical clearance would not matter.
Respondent 3	Think you would need a minimum of 15ft and is platform specific.
Respondent 4	At least be 30'-40' above the ground before using a UAV, otherwise a ladder can be used to access underside of bridge.
Respondent 5	Yes, you need about 15 under a bridge to do automated flights under the bridge. if doing manual flights under the bridge I think you can get by with about 8ft. I would say for the sides of bridges you need about 10ft of clearance. top side you don’t want to fly below 25-30 ft with traffic on the bridge.
Respondent 6	A low vertical clearance would not be an issue unless that bridge was over live traffic or dense vegetation.
Respondent 7	Yes, vertical clearance is a factor if you have to launch from beneath the bridge. Skydio requires at least 10 ft of clearance to launch.
Respondent 8	Depends on UAV capability. Most UAVs have proximity sensors which may limit use under bridges with very high-water level (say freeboard less than 8 feet). Vertical clearance over the bridge has never been an issue.
Respondent 9	See previous answer.

Table A-7: First-Round Survey Results Part 7

Q0	**Q7**
Please provide your name, affiliation, and email.	**Could the width of a bridge impact UAV-enabled bridge inspection? If so, what might the numerical threshold be? (e.g., if a bridge is >75 ft wide, UAV enabled bridge inspection may be inefficient.)**
Respondent 1	No.
Respondent 2	Again, it would depend on if pilot if flying BVLOS. If not, then width would not be an issue. If so, it would depend on UAV/controller signal strength.
Respondent 3	Should not be an issue.
Respondent 4	I don't believe the width would impact the use of UAV.
Respondent 5	just require more passes.
Respondent 6	Drones are great for wide bridges. We have never encountered an issue with the width of the bridge using our UAVs.
Respondent 7	Not a factor if topography and batter life are considered.
Respondent 8	Not if both the drone and the pilot are on the top of the structure. Width of the bridge can be an issue as it creates interference with connectivity if the pilot is on the topside and the UAV is flying underside or vice versa. I'd say anything wider than 50 feet +/- can be inefficient.
Respondent 9	Bridge width would likely have a minimal effect as long as the drone is in visual range.

Table A-8: First-Round Survey Results Part 8

Q0	**Q8**
Please provide your name, affiliation, and email.	**Could the “facility carried” or “feature under” a structure impact UAV enabled bridge inspection? (e.g., A structure carrying a railroad may not be suitable for UAV-enabled bridge inspection.)**
Respondent 1	Features under the bridge could possibly limit the use of a drone, as flights over pedestrians and traffic is not permitted.
Respondent 2	Yes. Traffic, pedestrians, and railroad are all factors to consider.
Respondent 3	Should not be an issue.
Respondent 4	Yes, if a vehicular road was under the bridge, you would need to implement lane closures so you're not flying over traffic. Same with RR. Over waterways seems more feasible.
Respondent 5	Railroad bridges are great candidates for drones. We used a drone on the inspection of Tren Urbano an elevated rail system in Puerto Rico. I think you will find rail agencies are not overly concerned about drones in the right of way. Bridges over water are also very good candidates for drone inspection. bridges over highways are doable but would recommend manual flight for these and fly between girders only.
Respondent 6	Railroads and live traffic directly under the bridge present challenges, but we have experience with both. Bridge inspections over railroads can be performed with the authorization and supervision of railway officials. The flights over live traffic can be remedied using traffic control.
Respondent 7	Roadways are a consideration, but it is my understanding that railroads are not concerned with drone inspections since the "tiny" drones are not a threat to trains.
Respondent 8	When feature under the structure carries active traffic and/or railroad, UAV cannot be used for underside inspection.
Respondent 9	We can't fly over designated national security sensitive facilities. Bridges within areas such as National Parks or certain reservoirs could also not be flown without special permission.

Table A-9: First-Round Survey Results Part 9

Q0	**Q9**
Please provide your name, affiliation, and email.	**Please list any type of structure that could potentially inhibit the use of UAV during bridge inspection. (e.g., the truss bridges maybe too complex and may not be suitable for UAV-enabled bridge inspection.)**
Respondent 1	Restricted air spaces, MTR's (military training routes).
Respondent 2	Any bridge with a Deck, Superstructure or Substructure grade less than a 7.
Respondent 3	Low lying bridges, bridges that are forested on both sides.
Respondent 4	I think any complex bridge could still utilize the UAV; it just becomes trickier to maneuver thru parts of the bridge.
Respondent 5	For prestress girders and segmental bridges, I believe you will be able to see CS3 and larger cracks/ defects. Not all CS2 cracks or defects will be visible in the photos. you will likely also get false CS2 indications. but perhaps you could alternate traditional inspections with drone inspections to mitigate this issue.
Respondent 6	Smaller, low clearance bridges over creeks pose an issue. Any bridge with a clearance lower than 6' might not be an efficient use of the drone.
Respondent 7	I do not know of a type of structure that would inhibit the use of drones.
Respondent 8	Bridges with closely spaced elements (spacing less than 6 feet) trigger the proximity sensors of a UAV. Bridge decks create interference between the UAV and pilot remote, and so, UAVs are not very efficient unless you have a clear line of sight between the pilot and the UAV.
Respondent 9	Bridges with tight girder spacing and congested diaphragms may limit access for photos. Complex structures, such as trusses, will not lend themselves to 3D modeling, but pictures can still be valuable.

Table A-10: First-Round Survey Results Part 10

Q0	**Q10**
Please provide your name, affiliation, and email.	**Is there any other characteristic that may impact a bridge's suitability for UAS-enabled bridge inspection?**
Respondent 1	Bridges near heavy vegetation which could interfere with drone flights near bridge components.
Respondent 2	Condition. See previous comment.
Respondent 3	As long as we have clearance and openings.
Respondent 4	Yes, the condition of the bridge. If the bridge is older and previously noted to have significant deterioration where measurements need to be made, then a UAV should not be used, and other means for the inspector to access should be made
Respondent 5	Transverse tinting (grooves) on the deck makes top of deck crack detection difficult. Makes automated crack detection impossible. Shadows on the bridge need to be planned around.
Respondent 6	It is helpful to have a high output light source to illuminate the underside of a bridge if is early morning, evening, or in a mountainous region that receives less natural light.
Respondent 7	Constant wind conditions during certain times of the year at coastal bridges should be considered (Marc Basnight and William B. Umstead, for example).
Respondent 8	
Respondent 9	Bridges in particularly high wind areas would be more challenging to inspect.

Table A-11: First-Round Survey Results Part 11

Q0	Q11
Please provide your name, affiliation, and email.	**Please tell us a little bit about yourself, what is your experience in UAVs and/ or in bridge inspection?**
Respondent 1	Bridge Inspector II- NCDOT Special Inspections; FAA Certified UAV pilot. Conducted numerous inspections using UAVs on various styles of bridges since certified.
Respondent 2	Bridge Inspector - 11 years - Primary focus on Fracture Critical, Movable Span and Ancillary Structure inspections. Licensed Remote Pilot for ~2.5 years.
Respondent 3	UAS Operations Manager for NCDOT...3D Scanned multiple types of bridges around state.
Respondent 4	I started my bridge inspecting career in 2005 as an assistant, the same year WIGINs was released at NCDOT. I became a TL in 2009 after passing my PE and taking the 2-week NHI course. I then started managing Wetherill's bridge inspectors in 2013. We've had consecutive years of NCDOT on call bridge inspection contract as well as several private and municipal bridge inspections.
Respondent 5	25 years bridge inspection experience across the southeast US. I have been utilizing drones for inspections since 2019. flown all types of bridges, simple highway bridges, to cable-stay bridges.
Respondent 6	I received my FAA Part 107 License in February of 2020 when I was a Survey Technician. I have collected aerial imagery for dozens of projects from SC, NC, TN, MD, VA, WV and GA. During my career, I have assisted with numerous bridge inspections including UAV data collection for our structures group.
Respondent 7	Fairly new pilot with drone inspection experience on roughly a dozen structures.
Respondent 8	I am an FHWA certified team lead inspector and a licensed bridge engineer with 5+ years of experience. I've utilized UAVs for inspection on 5-7 bridges, which had either railroads or creeks/rivers/sound under them. UAVs are a great tool for inspections of structures which are graded good. Their use is limited in tight spaces and are, therefore, ideal for bridges with open geography around them.
Respondent 9	The company has vast bridge inspection experience and has performed several drone inspections. Employee A- 30 years bridge inspection experience. Employee B - 20 years bridge inspection experience. Employee C - 30 years bridge construction experience, 5 year pilot.

B.1 APPENDIX B: SECOND-ROUND SURVEY RESULTS

Table B-1: Second-Round Survey Results Part 1

Q0	**Q1**	
Please provide your name.	**Please select any geographic features that may impact the use of UAV during bridge inspection. First-round survey responses are summarized below, along with the number of times each item was provided as a response. Please check the box next to all responses you agree with. You can also provide any new responses or comments in the box below the list.**	**Please provide additional responses or comments here.**
Respondent 1	Heavy vegetation/ tree areas (7 respondents), Live traffic (1 respondent)	From experience I've seen that heavy vegetation is the single most cumbersome item encountered while using UAV systems to inspect bridges.
Respondent 2	Heavy vegetation/ tree areas (7 respondents), FAA No-Flight Zones (4 respondents), Bridges over roadways (3 respondents), Overhead utilities (2 respondents), High ADT (1 respondent), Live traffic (1 respondent)	
Respondent 3	Heavy vegetation/ tree areas (7 respondents), FAA No-Flight Zones (4 respondents), Bridges over roadways (3 respondents), High ADT (1 respondent), Live traffic (1 respondent)	
Respondent 4	Heavy vegetation/ tree areas (7 respondents), FAA No-Flight Zones (4 respondents), Bridges over roadways (3 respondents), Low bridges over water (2 respondents), Overhead utilities (2 respondents), High ADT (1 respondent), Live traffic (1 respondent)	
Respondent 5	Heavy vegetation/ tree areas (7 respondents), Overhead utilities (2 respondents)	
Respondent 6	Heavy vegetation/ tree areas (7 respondents), FAA No-Flight Zones (4 respondents), Bridges over roadways (3 respondents), Low bridges over water (2 respondents), Overhead utilities (2 respondents), High ADT (1 respondent), Live traffic (1 respondent)	
Respondent 7	Heavy vegetation/ tree areas (7 respondents), Bridges over roadways (3 respondents)	

Table B-2: Second-Round Survey Results Part 2

Q0	**Q2**	
Please provide your name.	**Please select any utility features that may impact the use of UAV during bridge inspection. First-round survey responses are summarized below, along with the number of times each item was provided as a response. Please check the box next to all responses you agree with. You can also provide any new responses or comments in the box below the list.**	**Please provide additional responses or comments here.**
Respondent 1	Heavy vegetation (2 respondents)	
Respondent 2	Power lines/ overhead utilities (4 respondents), Utility in structure bays (2 respondents), Heavy vegetation (2 respondents), Radio frequency interference (1 respondent)	
Respondent 3	Power lines/ overhead utilities (4 respondents)	
Respondent 4	Power lines/ overhead utilities (4 respondents), Utility in structure bays (2 respondents), Heavy vegetation (2 respondents), Power stations (1 respondent), Guywires (1 respondent), Radio frequency interference (1 respondent), Diaphragms (1 respondent), Low freeboard (1 respondent)	
Respondent 5	Power lines/ overhead utilities (4 respondents), Guywires (1 respondent)	
Respondent 6	Power lines/ overhead utilities (4 respondents), Utility in structure bays (2 respondents), Guywires (1 respondent), Radio frequency interference (1 respondent)	Responses refer only to utility impacts.
Respondent 7	Power lines/ overhead utilities (4 respondents), Utility in structure bays (2 respondents)	

Table B-3: Second-Round Survey Results Part 3

Q0	**Q3**	
Please provide your name.	**Could you suggest a traffic volume carried on or under a bridge that would prohibit or substantially limit use of a UAV during bridge inspection? First-round survey responses are summarized below, along with the number of times each item was provided as a response. Please check the box next to all responses you agree with. You can also provide any new responses or comments in the box below the list.**	**Please provide additional responses or comments here.**
Respondent 1	Any amount is fine as long as UAS is not above live traffic (3 respondents)	
Respondent 2	Any amount could be a hinderance (2 respondents), Any amount could be fine as long as there is traffic control (1 respondent)	
Respondent 3	Any amount could be a hinderance (2 respondents), Any amount could be fine as long as there is traffic control (1 respondent), ADT>2000 (1 respondent)	Depends on what you are trying to accomplish. Top side deck inspection will take multiple passes if traffic is heavy.
Respondent 4	Any amount is fine as long as UAS is not above live traffic (3 respondents), Any amount could be fine as long as there is traffic control (1 respondent)	
Respondent 5	Any amount is fine as long as UAS is not above live traffic (3 respondents)	
Respondent 6	Any amount could be a hinderance (2 respondents)	This is a hard question to answer as there are many variables involved. Drones can be a distraction for drivers and increase the risks for accidents, especially in heavy / congested traffic.
Respondent 7	Any amount is fine as long as UAS is not above live traffic (3 respondents)	

Table B-4: Second-Round Survey Results Part 4

Q0	**Q4**	
Please provide your name.	**Would the length of the bridge or number of spans impact the usability of UAV during bridge inspection? If so, what are some numerical limits to these attributes? First-round survey responses are summarized below, along with the number of times each item was provided as a response. Please check the box next to all responses you agree with. You can also provide any new responses or comments in the box below the list.**	**Please provide additional responses or comments here.**
Respondent 1	Battery life and topography matter most, not bridge length and number of spans (2 respondents)	Batteries on currently employed drones last approximately 15 minutes before a change is required.
Respondent 2	Not important as long as pilot can stay close to the UAS (9 respondents), Battery life and topography matter most, not bridge length and number of spans (2 respondents)	
Respondent 3	Not important as long as pilot can stay close to the UAS (9 respondents), Not feasible to inspect bridge during flight, desktop view of images required (1 respondent)	
Respondent 4	Not important as long as pilot can stay close to the UAS (9 respondents), Battery life and topography matter most, not bridge length and number of spans (2 respondents)	
Respondent 5	Not important as long as pilot can stay close to the UAS (9 respondents), Battery life and topography matter most, not bridge length and number of spans (2 respondents)	
Respondent 6	Not important as long as pilot can stay close to the UAS (9 respondents), Battery life and topography matter most, not bridge length and number of spans (2 respondents)	
Respondent 7	Not important as long as pilot can stay close to the UAS (9 respondents)	

Table B-5: Second-Round Survey Results Part 5

Q0	**Q5**	
Please provide your name.	**Could the vertical clearance over and under the bridge impact UAV-enabled bridge inspection? If so, what might the numerical threshold be? First-round survey responses are summarized below, along with the number of times each item was provided as a response. Please check the box next to all responses you agree with. You can also provide any new responses or comments in the box below the list.**	**Please provide additional responses or comments here.**
Respondent 1	Vertical clearance does not matter (4 respondents)	
Respondent 2	Vertical clearance does not matter (4 respondents), Over/under the bridge for >200 ft would be an issue (1 respondent)	
Respondent 3	Depends on UAS (2 respondents), Manual flight minimum 8ft under bridge (1 respondent), Auto flight minimum 15 ft under bridge (1 respondent)	
Respondent 4	Depends on UAS (2 respondents)	
Respondent 5	Minimum 10 ft clearance to launch (1 respondent)	
Respondent 6	Depends on UAS (2 respondents), Minimum 15 ft under bridge (1 respondent)	Vertical clearance matters during launching if forced to launch beneath the bridge (due to vegetation, topography, etc.).
Respondent 7		

Table B-6: Second-Round Survey Results Part 6

Q0	**Q6**	
Please provide your name.	**Could the width of a bridge impact UAV-enabled bridge inspection? If so, what might the numerical threshold be? First-round survey responses are summarized below, along with the number of times each item was provided as a response. Please check the box next to all responses you agree with. You can also provide any new responses or comments in the box below the list.**	**Please provide additional responses or comments here.**
Respondent 1	No (5 respondents)	
Respondent 2	No (5 respondents), No, but depends on UAS and pilot (4 respondents)	
Respondent 3	No (5 respondents)	
Respondent 4	No (5 respondents)	
Respondent 5	No (5 respondents)	
Respondent 6	No (5 respondents)	
Respondent 7		

Table B-7: Second-Round Survey Results Part 7

Q0	**Q7**	
Please provide your name.	**Could the "facility carried" or "feature under" a structure impact UAV-enabled bridge inspection? First-round survey responses are summarized below, along with the number of times each item was provided as a response. Please check the box next to all responses you agree with. You can also provide any new responses or comments in the box below the list.**	**Please provide additional responses or comments here.**
Respondent 1	Can't fly over live traffic (5 respondents), Can't fly over pedestrians (2 respondents), Can't fly over national security sensitive facilities (1 respondent)	
Respondent 2	Can't fly over live traffic (5 respondents), Railroad authority need to be contacted (5 respondents), Can't fly over pedestrians (2 respondents), Can't fly over national security sensitive facilities (1 respondent), Bridges in national parks, certain reservoirs have required special permission (1 respondent)	
Respondent 3	Railroad authority need to be contacted (5 respondents), Can't fly over pedestrians (2 respondents), Can't fly over national security sensitive facilities (1 respondent), Bridges in national parks, certain reservoirs have required special permission (1 respondent)	
Respondent 4	Can't fly over live traffic (5 respondents), Railroad authority need to be contacted (5 respondents), Can't fly over pedestrians (2 respondents), Can't fly over national security sensitive facilities (1 respondent), Bridges in national parks, certain reservoirs have required special permission (1 respondent)	
Respondent 5	Can't fly over live traffic (5 respondents), Railroad authority need to be contacted (5 respondents)	
Respondent 6	Can't fly over live traffic (5 respondents), Railroad authority need to be contacted (5 respondents), Can't fly over pedestrians (2 respondents), Can't fly over national security sensitive facilities (1 respondent), Bridges in national parks, certain reservoirs have required special permission (1 respondent)	
Respondent 7		

Table B-8: Second-Round Survey Results Part 8

Q0	**Q8**	
Please provide your name.	**Please list any type of structure that could potentially inhibit the use of UAV during bridge inspection. First-round survey responses are summarized below, along with the number of times each item was provided as a response. Please check the box next to all responses you agree with. You can also provide any new responses or comments in the box below the list.**	**Please provide additional responses or comments here.**
Respondent 1	Bridges with tightly grouped elements (2 respondents)	
Respondent 2	Bridges with tightly grouped elements (2 respondents), Bridge condition <7 (1 respondent)	
Respondent 3	Bridges with tightly grouped elements (2 respondents), Smaller, low clearance bridges (2 respondents)	
Respondent 4		
Respondent 5	Bridges with tightly grouped elements (2 respondents), Smaller, low clearance bridges (2 respondents)	
Respondent 6	Smaller, low clearance bridges (2 respondents), Bridge condition <7 (1 respondent)	
Respondent 7		

Table B-9: Second-Round Survey Results Part 9

Q0	**Q9**	
Please provide your name.	**Is there any other characteristic that may impact a bridge's suitability for UAV-enabled bridge inspection? First-round survey responses are summarized below, along with the number of times each item was provided as a response. Please check the box next to all responses you agree with. You can also provide any new responses or comments in the box below the list.**	**Please provide additional responses or comments here.**
Respondent 1	Poor lighting conditions (2 respondents), Heavy vegetation (1 respondent)	
Respondent 2	Lower condition ratings (2 respondents), Poor lighting conditions (2 respondents), Strong winds (2 respondents), Heavy vegetation (1 respondent)	
Respondent 3	Lower condition ratings (2 respondents), Poor lighting conditions (2 respondents), Strong winds (2 respondents), Heavy vegetation (1 respondent)	
Respondent 4	Poor lighting conditions (2 respondents), Strong winds (2 respondents), Heavy vegetation (1 respondent)	
Respondent 5	Lower condition ratings (2 respondents)	
Respondent 6	Lower condition ratings (2 respondents), Poor lighting conditions (2 respondents), Strong winds (2 respondents)	Heavy vegetation was discussed previously. Poor lighting conditions could be mitigated. Winds are the biggest challenge.
Respondent 7		

C.1 APPENDIX C: Resource Assessment Tool for Effective UAV-Assisted Bridge Inspections

C.1.1 Introduction

Implementation of UAVs into an agency's inspection program should provide many benefits, but is an extensive undertaking that requires planning, resources, and capital investments [18]. As a result, there has been great interest in developing practices and tools that can aid in planning and optimizing the logistics, resources, and approaches used to support both conventional and UAV-enabled bridge inspection. Recently, research has been conducted to support decision-making regarding the capital investments for the acquisition of the most appropriate UAV platforms to be integrated into bridge inspection processes [19–22]. Another resource that could support the

effective planning of UAV-enabled inspections is a tool that equips inspection planners with knowledge of the required in-field inspection time and resources to support inspection activities for a given bridge. Such a tool could also be used to help optimize the inspection process with regard to time and efficient use of resources. In this study, a flight time estimator tool was developed that can

be used to support and justify UAV-assisted bridge inspections, as well as to maximize both time and cost savings. Using informed assumptions based on bridge geometry, pilot experience, and equipment used, the tool supports the development of optimal flight paths based on the geometry and positioning of structural elements of a bridge, establishes a range of recommended flight speeds for conducting reliable UAV-assisted bridge inspections based on the skill level(s) of the pilot(s) involved in the bridge inspections, and establishes a recommended range of wind speed and the corresponding standoff clearance information for safely conducting the UAV-assisted bridge inspections. These assumptions can be customized by agencies based on their personnel experience, equipment, environmental factors, and other experience. The tool also provides information on the number of batteries required to support a given UAV-enabled inspection approach as well as the corresponding estimated in-field inspection time. This tool should improve the planning and execution of the UAV-enabled bridge inspection process, since its output can be used to guide and optimize the inspection approach prior to the inspectors' site visit, to help size and select appropriate portable power sources, and to identify bridges where UAV-enabled inspection is or is not an effective choice. Given the vast range of bridge types and configurations, site conditions, personnel capabilities, and resources available to support UAV-enabled inspection, the tool was developed to be simple and customizable. Downloadable (at no cost) in Excel-based form, it is hoped that users will customize the tool to reflect their capabilities and to suit the type(s) of bridges they are inspecting. The following sections describe the development of the resource estimation tool, including assumptions required for use of the tool, experiments that were conducted to support the development of the tool, definitions that were established and adopted, and the application of the tool in a case study. Recommendations to support agency use of the tool are provided. The closing sections discuss the results and conclusions and provide recommendations for future work.

C.1.2 Literature Review - UAV as a Bridge Inspection Tool

The BIRM categorizes tools used by inspectors at bridge sites during bridge inspections into seven fundamental categories as inspection tools, cleaning tools, visual tools, measuring tools, access tools, documenting tools, and miscellaneous tools [5]. By deploying UAVs as assistive tools, it is projected that they can serve a multipurpose role as an inspection tool, a visual tool, an access tool, and a documenting tool [17]. In [16], the authors argued that, although presently, UAVs fail to provide the physical contact that most bridge inspections require, they can be cost-effective and time-efficient alternatives to conducting certain inspections. The work in [16] discusses the use of UAVs in terms of overall coverage and targeted coverage. In the former, a UAV is employed as the sole tool for conducting the bridge inspection whereas in the latter, based on past inspection reports and recommendations, a UAV is employed as a supplemental tool for inspecting specifically selected areas of the bridge.

Primary benefits touted by many researchers are improved safety for both inspectors and nearby traffic, ease of access to hard-to-reach areas, reduced inspection time, costs, and traffic impacts. Additionally, UAVs can utilize high-quality cameras to collect enhanced imagery data of bridge elements at close proximity. This assists in developing inspection reports and supports decision-making [11]. Although UAV-assisted bridge inspections show promise to provide these benefits, their integration into bridge inspections could result in negative consequences such as delays, increased costs incurred, and traffic safety issues, if not properly planned and executed [23]. For example, not having a clearly defined candidate bridge selection criteria, an optimal flight pattern, and/or a vague set of inspection objectives can negatively impact UAV-assisted inspections, resulting in the waste of logistic, monetary, and time resources. Some factors that can contribute to these negative impacts include the experience and expertise levels of pilots, adverse environmental conditions for bridge inspection, and the decision to use a UAV for the inspection of a bridge that exhibits characteristics rendering it an unsuitable candidate for UAV-enabled inspection. Prior to visiting the site, inspection teams must plan to ensure the appropriate access equipment and/or UAV components are available to support the completion of the inspection [18, 24].

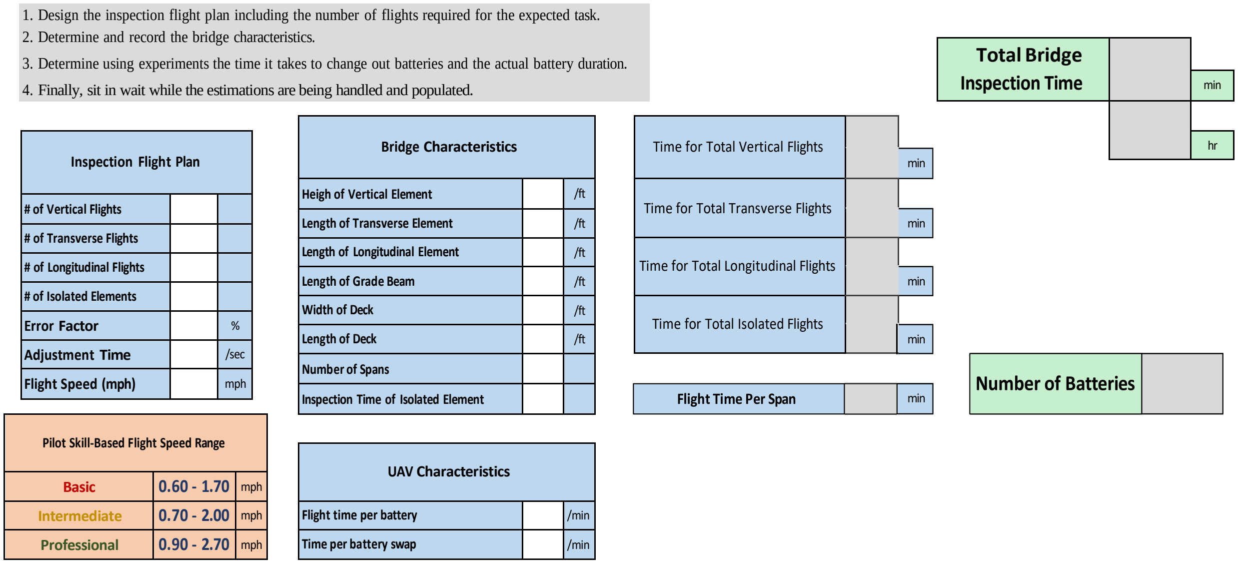
A survey response presented by the American Association of State Highway and Transportation Officials (AASHTO) in 2016 concluded that the bridge inspectors were able to reduce the inspection time by 6 hours and reduce the inspection costs by $4,350 using a UAV in an inspection of a standard bridge deck [14, 25]. Similarly, a comparative analysis conducted by the Minnesota Department of Transportation (MnDOT) in the second phase of a demonstration project over the Duluth's Blatnik multi-girder Bridge suggested that both time and cost savings are achievable through the use of UAVs in the bridge inspection process. In the demonstration, a traditional inspection involving access equipment components of UBITs, access ropes, personnel lifts, among others, lasted for 8 days and incurred an approximate cost of $59,000 which was referred to as a minimum cost [24]. In contrast, approximately 40% and 66% savings were reported for time and cost quotations respectively when UAVs were employed for this bridge inspection. MnDOT, upon completion of a three-phased UAV-assisted bridge inspection project, reported the potential of a 66% cost savings in conducting UAV-assisted bridge inspection when compared to the conventional practice [12].

In another study conducted by Oregon State University for Oregon DOT, a 20% reduction in in-field time was observed for bridge inspections when employing UAVs as an assistive tool [13]. This study also established an estimate that per every 20% savings in in-field time, a corresponding 20% decrease in equipment rental and traffic control costs could result [13]. In a detailed breakdown of the cost savings analysis, a total estimated savings of $10,000, which included $3,500 savings on traffic control, a $2,800 savings on equipment rental, and a $3,900 savings on personnel time were reported when UAVs were employed for bridge inspections.

C.1.3 Development of Flight Time Estimation Tool for UAV-Assisted Bridge Inspections

We have developed a time estimation tool for assessing the flight time of the UAVs for bridge inspection. A snapshot of the developed tool is shown in Figure C.1. The tool is also available as an Excel sheet at https://github.com/ACCESSLab/Resource-Assessment-Tool-for-Effective-UAV-Assisted-Bridge-Inspection. In order to develop this time estimation tool, we first conducted a series of field experiments comprising bridge inspections that were planned for the development of the flight time estimation tool for UAV-assisted bridge inspections. These field experiments were performed during several field trips to different identified bridge sites in the state of North Carolina, over a period of one year. Bridges included in the work to develop this tool were continuous steel multi-beam bridges with reinforced concrete decks. The experiments conducted included the following: 1) Determine appropriate flight paths for conducting time-efficient UAV-assisted bridge inspections and 2) Establish an acceptable range of flight speed considering different skill levels (as beginner, intermediate, and expert) of the pilots involved in the bridge inspection. Real-time measurements were recorded at the bridge site using a stopwatch during all these experiments. Also, these real-time recorded values were confirmed with the timestamps retrieved from the collection of videos that were recorded during the bridge inspections using the UAV platforms. This helped to reduce human-error possibilities during experimentation.

The results from these experiments were subsequently utilized to fine-tune the parameters necessary for developing the flight-time estimation tool for UAV-assisted bridge inspections. Detailed discussions about each of these experiments related to the development of the flight-time estimation tool are provided in the following subsections.



1. Design the inspection flight plan including the number of flights required for the expected task.
2. Determine and record the bridge characteristics.
3. Determine using experiments the time it takes to change out batteries and the actual battery duration.
4. Finally, sit in wait while the estimations are being handled and populated.

Inspection Flight Plan		
# of Vertical Flights		
# of Transverse Flights		
# of Longitudinal Flights		
# of Isolated Elements		
Error Factor		%
Adjustment Time		/sec
Flight Speed (mph)		mph

Pilot Skill-Based Flight Speed Range		
Basic	0.60 - 1.70	mph
Intermediate	0.70 - 2.00	mph
Professional	0.90 - 2.70	mph

Bridge Characteristics		
Heigh of Vertical Element		/ft
Length of Transverse Element		/ft
Length of Longitudinal Element		/ft
Length of Grade Beam		/ft
Width of Deck		/ft
Length of Deck		/ft
Number of Spans		
Inspection Time of Isolated Element		

UAV Characteristics		
Flight time per battery		/min
Time per battery swap		/min

Time for Total Vertical Flights		min
Time for Total Transverse Flights		min
Time for Total Longitudinal Flights		min
Time for Total Isolated Flights		min
Flight Time Per Span		min

Total Bridge Inspection Time		min
		hr

Number of Batteries	

Figure C.1. A snapshot of the developed flight time estimation tool. The blue cells are the required inputs, the orange cells provide guidance, and the green cells provide computed output values.

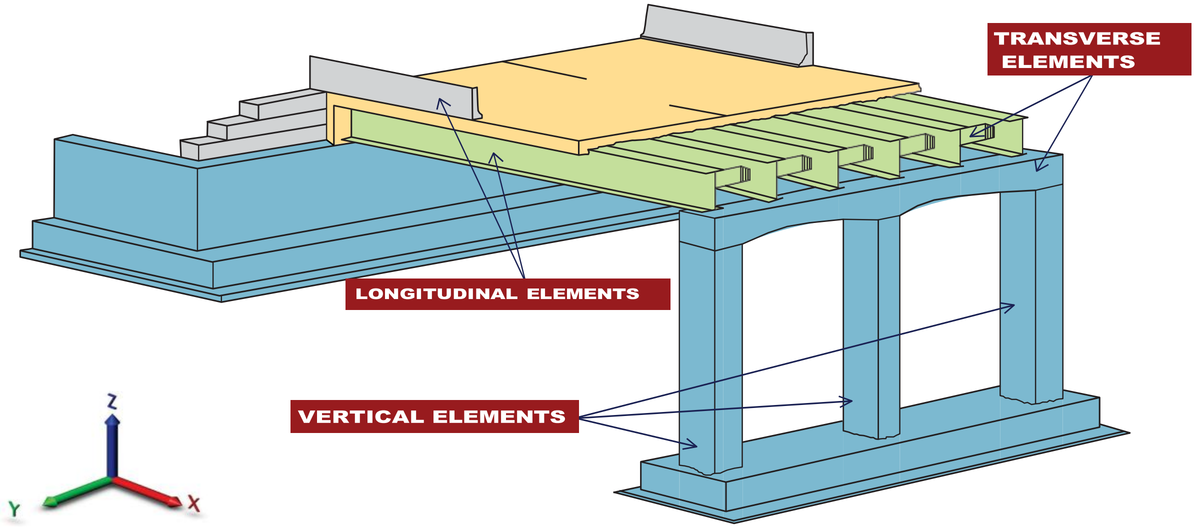


Figure C.2. Longitudinal, transverse, and vertical flight paths.

C.1.3.1 Inspection Flight Plan

In order to maximize the effectiveness of using UAVs and to estimate the flight times for the purpose of aiding the bridge inspection processes, and also based on experimental results obtained, the inspector and/or pilot need to carefully design flight paths to cover different elements of the bridge. Facing a side of the structure, three main flight paths were defined as longitudinal, transverse, and vertical following the 3D axes nomenclature as shown in Figure C.2. A fourth flight path, referred to as the targeted flight, was defined for navigation through the remaining areas of the bridge structure that were not captured under the above three.

- Longitudinal Flights: The longitudinal flight path traverses the bridge in the direction of traffic flow carried by the bridge, coinciding with the X-axis in a 3D coordinate system. Under this flight path definition, structural elements such as the deck, girders, girder beams, deck railings, and others are captured and inspected as shown in Figure C.2. Note that although diaphragms are oriented perpendicular to girders, they may also be best observed in longitudinal flights in bridges that are not particularly wide. Transverse Flights: Structural elements of the bridge that are typically oriented perpendicular to the direction of traffic carried by the bridge, along the ordinate (y-axis) of a 3D plane and interconnect longitudinal elements. As visualized in Figure C-2, this flight path covers the inspection of bridge elements like the pile caps and the grade beams.
- Vertical Flights: Referring also to Figure C.2, vertically erected elements that typically run perpendicular to the horizontal, are observed using the vertical flight category of the defined flight paths. Piles, piers, columns, bents, and abutments are typical types of elements that fall under this defined category.
- Targeted Flights: An additional flight path category, targeted flight, was created due to the fact that certain elements of the bridge could not be classified under the three basic paths defined above. Bearings and connectors are examples of such elements. UAVs can be used as a tool to inspect certain targeted areas of the bridge based on concerns raised in past inspection reports, inspection

requirements, or other recommendations. These target-specific flights can also be called targeted flights.

C.1.3.2 Flight Speeds Assessment based on Pilots' Skills

Obviously, due to varying human factors and experience levels, not all pilots can be said to have the same skill level with regards to flying UAVs and conducting bridge inspections. Due to this difference, experimental test flights were conducted over a selected bridge with characteristics as presented in Table C.1 to establish recommendations on the range of flight speed for each categorized pilot's skill level in a UAV-assisted bridge inspection process. In setting up the experimental test flights, three different pilots with different skill levels, namely basic, intermediate, and professional were employed.

Table C.1. Characteristics of the Bridge

Bridge Data		
Height of Vertical Element	35.00	ft
Length of Transverse Element	34.00	ft
Length of Longitudinal Element	223.00	ft
Number of Isolated Elements	4	
Number of Spans	10	

In the experiment conducted, three pilots with varying piloting skills were tasked with inspecting a bridge. Pilot 1 had a basic skill rating, Pilot 2 had an intermediate skill rating, and Pilot 3 was professionally skilled. The three pilots took turns performing an element-level inspection of selected elements in a span of the bridge under the same persisting environmental conditions. A span comprised two piles, four girders, a single grade beam connecting adjacent piles, a single pile cap with four installed bearings, and the deck. During this experiment, for each pilot, four flights were conducted over 1 of the 2 vertical elements, four flights over the cap (transverse element) and four flights over the girders (longitudinal element). After repeating the process for two times, the total time each pilot took to successfully complete the designed inspection pattern was computed and presented in Table 2. The results in Table C.2 can be further improved by observing and measuring the flight performance of more pilots over different bridges.

Table C.2. Inspection time for each pilot in seconds for two trials.

Element	**Pilot 1**		**Pilot 2**		**Pilot 3**	
	1st	2nd	1st	2nd	1st	2nd
Pile Face 1	50	47	46	41	32	32
Pile Face 2	50	51	44	42	35	34
Pile Face 3	46	45	42	43	30	33
Pile Face 4	46	48	40	41	34	30
Cap Face 1	35	33	25	28	23	24
Cap Face 2	30	30	25	25	25	25
Cap Face 3	35	31	32	33	27	30
Cap Face 4	30	33	34	34	30	29

Girder 1	95	96	75	76	52	50
Girder 2	100	101	77	75	50	48
Girder 3	100	97	74	73	51	50
Girder 4	96	93	72	68	47	52
Total Time	**713**	**705**	**586**	**579**	**436**	**437**

With bridge characteristics such as element dimensions at hand, and having computed the corresponding flight time per pilot, the respective inspection speed for each pilot was computed. Given the influence of factors such as the type of UAV used, persistent weather conditions, and the complexity of the inspection pattern on the recommended flight speed for each pilot's skill level, we incorporated a tolerance range of ±50% into the flight speeds. This resulted in flight speed ranges presented in Table C.3. Agencies using this tool could improve the recommended flight speed ranges by conducting these speed tests with multiple of their own pilots per skill level at varying environmental conditions over different bridges with desired characteristics.

It was observed that the time taken for navigating between successive element inspections, referred to as adjustment time, reduced with increasing pilot skill level. That is, the basic skilled pilot averaged an adjustment time of 25 seconds whereas the intermediate and professionally skilled pilots averaged 20 seconds and 10 seconds, respectively. Although their adjustment times differed, it was observed that all three pilots averaged 15 seconds in inspecting a single bearing.

Table C.3. Recommended Flight Speed Range per Pilot Skill

Recommend Flight Speeds		
	Range	Unit
Basic	0.60 − 1.70	mph
Intermediate	0.70 − 2.00	mph
Professional	0.90 − 2.70	mph

C.1.3.3 Adoption of Wind Speed Limits

Wind speed is one of the major factors to be considered when conducting a UAV-assisted bridge inspection to ensure the safety of an employed UAV platform, inspection personnel, road traffic vehicles and the public around the inspection site. Test results presented on the maneuverability of UAVs were detailed in [26]. It was observed in the experiments conducted that at a minimum clearance of 3 ft from a target spot and maximum constant wind speed of 15 mph, a competent pilot can safely conduct a UAV-assisted bridge inspection. In [27], a conclusion was drawn by the authors after investigating the effectiveness of micro-UAVs for image data collection. It was stated that at 0 − 5 miles per hour (mph) wind speeds, high-quality data were repetitively obtained. Furthermore, Otero et al. in [26] investigated the effective standoff clearance and corresponding wind speeds and gusts at which collected UAV data are attentive to detail. An estimated standoff clearance of 0.3 m (1 ft) for wind speed less than 7 mph (11 km/h) and wind gusts less than 10 mph (16 km/h) was reported in their work.

With these reported works as a benchmark, in the experiments we conducted, a conscious effort was made to carry out all inspections within these limits. Inspection results from these experimental flights were compared and a satisfactory conclusion was drawn. It was observed that for a professional pilot with expert flying skills, at wind speed range between 0 − 5 mph, inspection outputs remained unchanged. A standoff clearance of 0.3 m (1ft) was established based on previous works and the experience of pilots supporting this study.

C.1.3.4 Error Factor

Practically, there are always events, circumstances, and unfavorable conditions that can affect the inspection process, often causing a scheduled inspection to extend beyond the estimated time. These include conditions such as harsh, intermittent wind speeds, which may lead to intermittent breaks in the inspection process, delays in battery charging and swaps, and the need to rescan a certain face or element, among other factors. Each of these events will negatively affect the overall bridge inspection time. As a result, an adjustable error factor was integrated into the estimation tool to cater for such uncertainties. In the case study presented in this paper, we have considered an error factor of 30%, although as agencies would work to tailor the tool to their own experience and preferences, this factor would be subject to the inspection conditions and the experience of pilots and inspectors.

C.1.3.5 Bridges with Dissimilar Structural Elements

The flight time estimation tool in this work is developed based on the assumption that the inspection process is conducted in a span-by-span sequence. Given this information, and assuming that wind speed, pilot skill level, and traffic conditions remain constant during the inspection, we can estimate the total flight time for inspecting the entire bridge by scaling up the time required for a successful single-span inspection by the number of spans in the structure. In cases where a bridge structure has non-identical elements and spans, we can adopt one of the following two methods:

- If the ratio of the shortest element's height/length to the tallest element's height/length is greater than 90%, then the tallest element's measurement should be used.
- Otherwise, an average of all elements throughout the structure should be used.
- Use the tool to calculate the estimated flight time for each span separately and then add them up to find the total inspection time.

C.1.4 Case Study

To demonstrate the application and effectiveness of the flight time estimation tool, the tool was used to inspect a selected steel continuous multi-beam bridge with a reinforced concrete deck, shown in Figure C.3. The bridge is located 50 ft south of the junction with SR1606 and carries North Carolina Highway 22 in Moore County, NC, over the Deep River in the High Falls community. The bridge has 10 identical spans with a total stretch of 200.56 m (658 f t) with reinforced concrete guardrails along the edges of the superstructure. The bridge has a maximum span of 68 m (20.73 f t) and a deck width out-to-out of 10.36 m (34 f t). A span of the bridge has 4 girders, 4 fixed bearings, reinforced concrete deck, standard joint, 2 reinforced concrete columns and a reinforced concrete pier cap. Table C.4 presents the required structural data for using this tool.

Figure C.3. A steel continuous multi-beam bridge with a reinforced concrete deck that was used as a case study to apply the developed tool.

C.1.4.1 Time Estimation

In this use case, we assumed that a pilot with a professional skill level is employed, capable of flying a UAV at a speed of 2.50 mph for data collection, provided that the wind speed remains within the accepted, safe range.

Table C.4. Flight Time Estimation

Flight Time Estimator		
	Number	Time /s
Vertical Flights	8	245.51
Transverse Flights	8	229.53
Longitudinal Flights	8	486.08
Targeted Flights	4	60.00
Standalone Flights	0	0.00
Flight Time per Span		1021.52
Error Factor		30%
Total Inspection Time		3.69 hr

As shown in Table C.4, a total of 28 flights were designed based on the structure of the bridge. The breakup of these flights is presented in Table 1, 8 of the 24 flights were vertical flights, 8 were longitudinal flights, 8 were transverse flights, and 4 individual flights for each of the 4 bearings. These do not include the deck, as during this case study, the bridge was open to traffic, preventing us from flying over the bridge. If the bridge were closed to traffic and we were able to use the UAV for deck inspection, we should have added 1 or 2 longitudinal flights for each span, depending on the flight height to scan the deck. The flight time was calculated based on the size of bridge elements for each span (presented in Table 3) and the flight speed of 2.50 mph, selected based on the “professional” skill level of the pilot. A maximum error of 30%

was assumed for uncertainties.

C.1.4.2 Battery Estimation

Based on the resulting total inspection time and the flight time per battery of the specific UAV platform, the flight time estimator was also used to estimate the number of batteries, assuming only 90% of the battery capacity is usable, for inspection of the selected bridge. Table C.5 corresponds to this estimation.

Table C.5. Battery Estimation

Total flight time for bridge inspection	3.69	hours
Flight Time per Battery	20.00	min
Number of Batteries	12	

C.1.4.3 Discussion of Results

By setting the adjustment time to 15 seconds and pairing this input with selected appropriate operating conditions, a total of approximately 3 hours and 42 minutes was estimated. The 12 number of batteries estimated above in Table 5 does not indicate that it will be necessary for the inspection team to prepare for the inspection by obtaining 12 individual batteries. Rather, this information can be used to size and select a suitable energy storage device that can best handle and provide the required cycle of charged batteries onsite during the inspection process given the principal number of batteries that comes with a selected platform. For example, in this case, fewer batteries could be used if suitable charging equipment is available to charge certain batteries while others are being used.

C.1.5 Conclusion

In this research work, an estimation tool was developed that aids in the planning for effective UAV-assisted bridge inspections. The tool can be adjusted for different bridge characteristics and enables bridge inspectors to plan the required logistics ahead of time during the pre-inspection stage of a UAV-assisted bridge inspection. The tool supports the inspector and/or pilot in assessing the inspection time and costs, as well as the required time for lane closures for bridge inspections. In development of the tool, the reports on inspection costs and times for conventional bridge inspections were reviewed in the context of analyzing the potential benefits of deploying the UAVs for bridge inspections. Furthermore, a set of experiments was conducted to first establish definitive flight paths, based on the bridge types and different structural components, followed by establishing a range of recommended parameters for the developed tool, such as the flight speed during the inspection, based on different categories of pilot skill levels. The need to incorporate an error margin was realized during the experimentation stage of this work and was subsequently included. Additionally, flexibility was considered for bridges with dissimilar structural elements in different spans by establishing selection criteria.

The developed resource estimation tool was applied in a case study to a steel continuous multi-beam bridge with a reinforced concrete deck with 10 identical spans located in Moore County, NC. In this case study, the tool estimated 3.69 hours is the required time to complete a full bridge inspection of this structure using a UAV as the sole inspection tool. Additionally, the corresponding number of batteries that best satisfies this time requirement was also estimated by the tool. This information, obtained prior to an in-field inspection, assists bridge owners and inspectors in planning and evaluating the applicability and importance of the integration of UAVs into bridge inspections.

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