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Synthesis of Capabilities, Opportunities, and Research Needs in UAS Technology for High-Precision Bridge Inspection

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16. Abstract
This report evaluates the potential role of camera-equipped unmanned aerial systems (UAS) as well as other forms of reality-mapping solutions in supporting bridge inspection practices for the Illinois Department of Transportation (IDOT). Traditional bridge inspections can require substantial labor, specialized access equipment, traffic control, and inspector exposure to hazards such as working at height, near live traffic, and over waterways. Camera-equipped UAS offer opportunities to improve visual access, reduce reliance on access-intensive equipment, minimize traffic disruption, and enhance inspection documentation. This report synthesizes federal and state case studies, regulatory requirements, emerging research, cost considerations, and IDOT bridge inventory characteristics to evaluate where UAS-based inspection can provide the greatest practical value. The findings indicate that camera-equipped UAS are most beneficial for routine visual inspection, rapid assessment, bridge deck screening, and documentation of difficult-to-access components, but are not a universal replacement for conventional methods, particularly for inspections requiring hands-on evaluation. The report also reviews emerging technologies, including autonomous navigation, computer vision-based 3D reconstruction with images and videos, artificial intelligence-assisted damage detection, automated reporting, and complementary sensing tools such as 360-degree cameras. A preliminary benefit-cost analysis and inventory-level prioritization framework are presented to identify bridge scenarios where camera-equipped UAS deployment may offer the greatest benefits in safety, accessibility, efficiency, cost-effectiveness, and inspection quality. Overall, the report recommends that reality-mapping solutions be integrated into a broader digital inspection program for IDOT, supported by targeted pilot studies, updated regulatory and cost assumptions, quality assurance protocols, and careful selection of high-value bridge inspection scenarios.

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Unmanned Aerial System (UAS), Drones, UAS-Assisted Bridge Inspection, Condition Assessment, Digital Twins, Bridge Inspection Safety, Visual Inspection, Image-Based Assessment

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EXECUTIVE SUMMARY

The Illinois Department of Transportation (IDOT) manages a large inventory of existing bridges that must be inspected regularly to ensure public safety and maintain infrastructure performance. Traditional bridge inspection can require substantial labor, specialized access equipment, traffic control, and inspector exposure to hazards such as working at height, working near live traffic, and accessing areas beneath or around bridge components. Unmanned aerial systems (UAS) offer an opportunity to support bridge inspection by improving visual access, reducing dependence on under-bridge inspection trucks and other access-intensive equipment, minimizing traffic disruption, and enhancing documentation of bridge conditions.

This report evaluates the potential role of camera-equipped UAS as well as other reality-mapping solutions, such as 360-degree and smartphone cameras, in IDOT bridge inspection through a synthesis of federal and state case studies, regulatory requirements, emerging research, cost considerations, and inventory-level bridge characteristics. The report first reviews the regulatory context for UAS-based inspection, including FAA Part 107 requirements, anticipated developments related to beyond visual line of sight operations (BVLOS), and IDOT's UAS Program Manual. These regulations establish important requirements related to remote pilot certification, airspace authorization, operations near people and traffic, visual line of sight (VLOS), crew roles, mission documentation, and safety procedures.

The review of previous case studies indicates that camera-equipped UAS are most beneficial for routine visual inspection, rapid assessment, bridge deck screening, and documentation of components that are difficult or unsafe to access using conventional methods. Camera-equipped UAS can be particularly valuable for bridges over waterways, bridges with high vertical clearance, and structures where conventional access would require lane closures or under-bridge inspection vehicles. However, camera-equipped UAS are not a universal replacement for conventional inspection. Their benefits are more limited for bridges with easy ground access and for inspection types requiring hands-on evaluation, such as in-depth, fracture-critical, or special inspections. UAS-based thermal imaging can support rapid bridge deck delamination screening, but follow-up verification using conventional nondestructive evaluation or hands-on methods may still be required.

Several technical and operational considerations are critical for successful camera-equipped UAS deployment. Important platform-selection factors include size, payload capacity, camera resolution, focal length, upward-looking gimbal capability, lighting, obstacle avoidance, collision tolerance, global navigation satellite system (GNSS)-denied hovering capability, resistance to magnetic interference, and data security. Quality assurance procedures are needed to ensure that UAS-collected imagery provides adequate coverage, resolution, viewing angles, illumination, and overlap to support reliable defect identification, documentation, and, when applicable, 3D reconstruction.

This study also reviews data-processing and reporting workflows for UAS-based inspection. Optical images and videos remain the most common data type, but thermal imagery, LiDAR 3D point clouds, computer vision image-based and video-based 3D point clouds, and AI-assisted damage detection and severity assessment are increasingly relevant. Image-based 3D reconstruction and virtual

inspection can improve spatial understanding and documentation, while AI-assisted image, thermal, and point-cloud processing may help reduce manual review and report-generation efforts. However, engineering judgment remains essential for interpreting defects and making final inspection conclusions. Emerging research on autonomous navigation, GNSS-denied localization, quality-aware mission planning, digital twins, automated reporting, and vision-language models suggests strong potential for future improvement.

A preliminary benefit–cost analysis indicated that camera-equipped UAS can substantially reduce inspection cost compared with access-intensive methods such as under-bridge inspection trucks when applied to suitable bridge scenarios, particularly for routine visual inspections. However, the economic advantage depends strongly on bridge type, access conditions, inspection objective, equipment selection, crew configuration, and UAS utilization rate. Complementary technologies, especially 360-degree cameras mounted on handheld poles, may provide a practical and economical alternative for bridges with reasonable ground access. These tools can support rapid visual documentation and broad scene capture with lower deployment complexity and should be considered in future pilot studies and digital inspection programs.

An analysis of three camera-equipped UAS inspections conducted in Illinois is also presented. The selected bridges represent different structure types, condition ratings, operational environments, and structural scales, enabling a comprehensive comparison of camera-equipped UAS performance across a range of inspection scenarios. Describing the data collection procedures and the lessons learned from each inspection supports the evaluation of the feasibility, advantages, and limitations of UAS-assisted bridge inspection and provides practical insights that can support the future implementation of UAS technologies in IDOT bridge inspection programs.

Finally, the report proposes an inventory-level prioritization approach to identify bridges where camera-equipped UAS deployment is likely to provide the greatest practical value. Candidate prioritization factors include average daily traffic, detour length, highway type, service beneath the bridge, vertical clearance, bridge length, and bridge width. The resulting rating framework is intended as a screening tool rather than a definitive decision rule and can help IDOT identify bridges or groups of bridges where UAS-based inspection may offer the greatest improvements in safety, accessibility, efficiency, cost-effectiveness, and inspection documentation. Overall, the report concludes that camera-equipped UAS should be integrated as part of a broader digital inspection program, with future pilot studies focused on high-value bridge scenarios, updated regulatory and cost assumptions, quality assurance protocols, and complementary sensing technologies.

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CHAPTER 1: INTRODUCTION

BACKGROUND

To ensure safety and uninterrupted functionality, the Illinois Department of Transportation (IDOT) inspects a sizable inventory of bridges on public roads in accordance with the National Bridge Inspection Standards (NBIS). This is a resource-intensive process, as it involves significant labor, specialized equipment, and traffic control measures, and it also places inspectors in potentially hazardous situations while they work near live traffic or at height.

Recent technological advancements in robotics and artificial intelligence have provided new opportunities to improve bridge inspections and reduce associated costs (Lin et al., 2021). The latest research, along with syntheses prepared by the Federal Highway Administration (FHWA), has shown that camera-equipped unmanned aerial systems (UAS) can lower traffic control needs, reduce reliance on under-bridge inspection vehicles, lifts, and rope-access teams, and improve inspection reliability and safety by limiting personnel risk exposure while providing visual access to hard-to-reach structural details. A final rule issued by the FHWA in 2022 updated the NBIS to incorporate these technological advancements, including the use of UAS in bridge inspections. This final rule recognizes UAS as a tool to improve inspector access to visually challenging areas, minimize the use of heavy access equipment, and reduce the time inspectors spend working adjacent to traffic. It also defines requirements for UAS-assisted visual inspections and rules governing public aircraft operations. The American Association of State Highway and Transportation Officials (AASHTO, 2025) has also developed guidelines for UAS applications for bridge inspections, which identify the practical considerations for UAS-based inspection, including organizational structure and workflow, UAS selection, UAS personnel training, UAS-based inspection methods, and data management. With continuing legal and technical developments, such as the FHWA's policy direction and the proposed AASHTO guideline for UAS-based element-level bridge inspections (National Academies of Sciences, Engineering, and Medicine [NASEM], 2024), the growing role of camera-equipped UAS in inspections is increasingly clear.

Despite these advancements, challenges remain before camera-equipped UAS can be fully integrated into routine bridge inspection workflows. Questions persist regarding compliance with Federal Aviation Administration (FAA) regulations, inspection applicability across different bridge types and inspection objectives, appropriate UAS selection, quality assurance, safety considerations, data processing methods, cost-effectiveness, and implementation challenges.

OBJECTIVES AND SCOPE

The objective of this report is to systematically assess the potential for reality-mapping solutions, including camera-equipped UAS, 360-degree cameras, and smartphone cameras, to enhance IDOT bridge inspections. Specifically, this report synthesizes findings from previous research, state and federal implementation efforts, and emerging academic studies to evaluate the opportunities and limitations of UAS-assisted bridge inspection. The report first reviews FAA regulations governing UAS operations to establish the regulatory context for reality-mapping-based bridge inspection. It then synthesizes findings from previous case studies, summarizing considerations related to inspection types, target structures, UAS selection, crew members, quality assurance practices, and safety management during data collection. Subsequently, the report summarizes the data analysis and reporting process for UAS-based inspection practices. Then, a discussion of the advantages and challenges associated with UAS-based bridge inspection is provided to summarize the key opportunities, limitations, and lessons learned identified from previous studies and practical implementations. Emerging research on improving the efficiency, quality, and capabilities of UAS-based bridge inspection is then reviewed to highlight future opportunities and technological developments. Subsequently, a benefit–cost analysis is conducted to compare UAS-based inspection approaches with conventional methods and other digital inspection technologies. Finally, the report analyzes the IDOT bridge inventory, proposes considerations for bridge selection, and develops a rating framework to evaluate the applicability of UAS-based inspection across different bridge scenarios. Overall, this report aims to provide a comprehensive assessment of the applicability, technical and practical considerations, opportunities, and limitations of UAS-assisted bridge inspection to help shape potential future research projects and implementable outcomes, such as the development of a UAS-assisted bridge inspection program for IDOT.

REPORT OUTLINE

The remainder of this report is organized as follows. Chapter 2 summarizes the regulatory context for UAS-based bridge inspection, including FAA and IDOT requirements. Chapter 3 reviews state and federal case studies on UAS-based data collection, while Chapter 4 discusses data types, processing workflows, and reporting approaches. Chapter 5 summarizes the main advantages and challenges of UAS-based bridge inspection. Chapter 6 reviews emerging research and complementary technologies for advancing digital inspection workflows. Chapter 7 presents a preliminary benefit–cost analysis, and Chapter 8 develops an inventory-level prioritization framework for identifying bridges where camera-equipped UAS may provide the greatest value. Chapter 9 presents field demonstrations on selected Illinois bridges, and Chapter 10 summarizes the report’s conclusions and recommendations for future IDOT implementation.

CHAPTER 2: REGULATIONS ON UAS

INTRODUCTION

The Federal Aviation Administration (FAA) is the federal agency responsible for regulating and overseeing civil aviation operations in the United States. To ensure the safe integration of unmanned aerial systems (UAS) into the National Airspace System, the FAA establishes operational requirements covering pilot certification, aircraft operation, airspace authorization, and safety procedures. Currently, Part 107 provides the primary regulatory framework for small UAS operations, including many UAS-based bridge inspections. In addition, the emerging Part 108 regulation is expected to significantly influence future UAS-based bridge inspection practices by enabling broader beyond visual line of sight (BVLOS) operations. In addition to FAA regulations, IDOT has developed a UAS Program Manual (IDOT, 2025) to provide guidance on the implementation and management of UAS operations within IDOT programs. The regulatory decision-making framework for UAS-based bridge inspection is presented in Figure 1, with the related regulations summarized in this chapter.

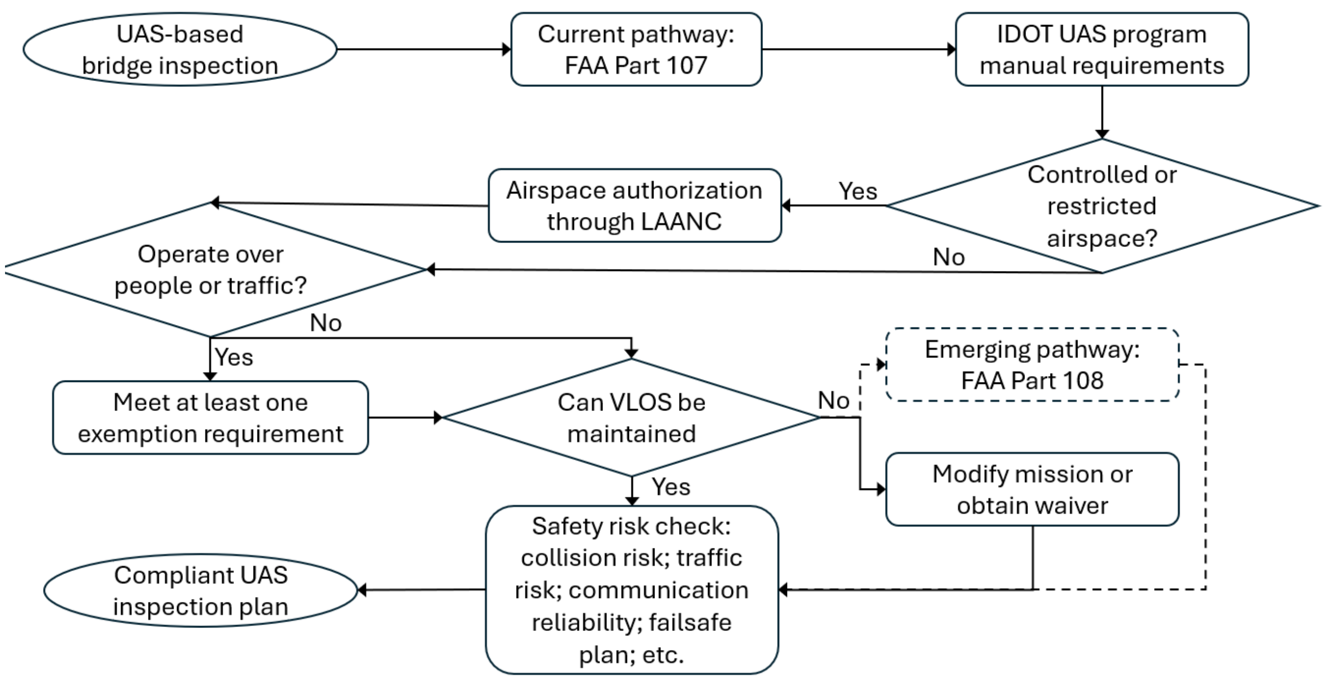


Figure 1. Diagram. Regulatory decision-making framework for UAS-based bridge inspection.

Source: Authors

FAA PART 107

FAA Part 107 (FAA, 2020) is the primary regulatory framework governing the commercial operation of small UAS in the United States. Introduced in 2016, Part 107 establishes requirements for pilot certification, aircraft registration, operational limitations, and safety procedures for UAS weighing less than 55 lb, which includes most UAS platforms used for bridge inspection. The key considerations for bridge inspection operations under Part 107 are summarized below.

Remote Pilot Certification

Most state DOTs choose to operate their UAS programs under FAA Part 107, which requires the UAS operator to hold a Part 107 Remote Pilot Certificate. To obtain the certificate, applicants must pass the FAA Aeronautical Knowledge Test, which covers topics including airspace classification, aviation weather, emergency procedures, operating requirements, radio communication procedures, and aeronautical decision-making. The certification requirement helps ensure that UAS operators possess sufficient knowledge to conduct safe and compliant inspection missions.

Airspace Authorization

When target bridges are located within controlled airspace due to nearby airports and airspace restrictions, UAS operations require FAA authorization prior to flight. Such authorization is commonly obtained through the Low Altitude Authorization and Notification Capability (LAANC) system.

Operations over People and Traffic

Bridge inspections frequently occur above traffic, making regulations regarding operations over people and moving vehicles particularly important. Under FAA Part 107, operations over uninvolved people and sustained flight over moving vehicles are generally prohibited unless specific requirements are met. Relevant exemptions for bridge inspection include:

- **Restricted-access sites:** Certain operations are permitted within closed or restricted-access areas where access is controlled and affected individuals are aware of UAS operations. For bridge inspections, this often requires traffic control measures or temporary lane closures so that only authorized inspection personnel are within the operational area.

- **People under covered structures or inside stationary vehicles:** Operations over individuals protected by covered structures or inside stationary vehicles are permitted, although such scenarios are uncommon in bridge inspection applications.

- **Category 1 UAS:** UAS weighing ≤ 0.55 lb, including payload, and without exposed rotating parts capable of causing lacerations may conduct operations over people under certain conditions.

- **Category 2 and Category 3 UAS:** UAS weighing > 0.55 lb may operate over people if they meet FAA-defined injury threshold requirements and manufacturer compliance documentation requirements. Category 3 operations have additional restrictions and are generally limited to restricted-access sites.

- **Category 4 UAS:** UAS possessing an FAA airworthiness certificate under Part 21 and operated according to approved operating limitations may conduct operations over people. Such UAS are currently uncommon in bridge inspection applications because FAA airworthiness certification is rarely pursued for commercial inspection platforms.

Visual Line of Sight (VLOS)

Under Part 107, the remote pilot or visual observer must maintain unaided visual line of sight to the UAS during operation. This requirement can be challenging for bridge inspections conducted beneath large bridges, around structural obstacles, or within confined regions where structural components may obstruct visibility. In some cases, waivers may be obtained to permit operations beyond standard VLOS requirements. In addition, new regulations governing BVLOS operations are currently under development and are expected to provide a more standardized framework for such operations, as discussed in the next section.

FAA PART 108

FAA Part 108 (FAA, 2025) is a recently proposed regulatory framework intended to enable routine and scalable BVLOS UAS operations through standardized regulations rather than through case-by-case waivers under Part 107. Although the rule is still in the public comment period, it reflects a trend toward more flexible UAS operations, which could further support bridge inspection applications. In particular, the proposed framework includes several provisions that are highly relevant to bridge inspection scenarios.

For bridge inspection, Part 108 could significantly expand operational flexibility by enabling routine BVLOS bridge inspections without repeated waiver applications. In addition, the proposed framework introduces shielded operations, in which UAS are permitted to operate BVLOS within 50 ft of a shielding structure and below a specified vertical boundary relative to that structure, using the structure itself to reduce collision risk with manned aircraft. Such provisions align well with common bridge inspection scenarios involving flights beneath bridge decks or near structural components. The proposed rule also emphasizes requirements related to detect-and-avoid capability, communication reliability, strategic deconfliction, and advanced localization systems, all of which are critical for safe operations in confined bridge environments.

IDOT UAS PROGRAM MANUAL

IDOT's UAS Program Manual is a recently published manual that supports UAS-related activities and programs within IDOT. It establishes additional requirements beyond the FAA requirements. Key manual provisions that affect UAS-based inspections are summarized below:

- More detailed UAS roles are defined, including UAS program manager, chief remote pilot, remote pilot-in-command (RPIC), and visual observer.
- At least one visual observer is required. The only exception is when critical safety-related information is needed in real time and when a lack of access to UAS imagery or data could further compromise the immediate safety or security of workers, the public, or critical infrastructure.

- Pilot currency rules require three operational missions or one practice mission with at least three takeoffs and landings every 90 days. In addition, pilots must demonstrate proficiency to the area UAS chief remote pilot every two years.

- Operation time is restricted, allowing an RPIC to operate a UAS up to six hours in a 24-hour period. An extension to this limit may be approved by the UAS program manager or designee.

- A flight record requirement mandates that all UAS missions conducted with department UAS be recorded in the department's authorized software, currently AirData.

- Additional safety requirements include pre-mission safety briefings, safety-enhancement features, traffic safety, and incident reporting.

CREW MEMBER QUALIFICATIONS AND REQUIREMENTS

Appropriate qualifications for the personnel involved in UAS-based bridge inspection are crucial for ensuring both safety and inspection quality. Although the minimum legal requirement under FAA Part 107 is the presence of a single certified RPIC, almost all the reviewed bridge inspection case studies employed at least two crew members.

In previous case studies, two additional supporting roles were commonly used. The first is the bridge inspector, who monitors the live video stream from the camera-equipped UAS and identifies potential defects either on-site or remotely (Darby and Gopu, 2018; Wells and Lovelace, 2021). For UAS platforms that allow separate control of flight maneuvering and camera orientation, a common practice is to assign the pilot responsibility for UAS movement while the bridge inspector controls the camera and performs defect identification (Michael Baker International, 2017; Neubauer et al., 2021). In such cases, the bridge inspector also serves as the sensor operator, according to AASHTO (2025) guidelines. Effective communication between the pilot and inspector is critical in such applications to ensure efficient image collection and accurate targeting of areas of interest. Most case studies included an inspector, allowing the pilot to focus primarily on safe flight operation while the inspector performs engineering assessments.

The second role is the visual observer, who assists the pilot by maintaining awareness of the UAS position, surrounding environment, and potential risks (Ni and Plotnikov, 2019; Bridge and Ifju, 2018). Although visual observers are less commonly reported than inspectors, they can play an important role in challenging inspection scenarios involving confined spaces, obstructed visibility, or complex structural environments. In addition, the IDOT UAS Program Manual (IDOT, 2025) requires that UAS missions include at least one pilot and one visual observer. Operations without a visual observer are only permissible when critical safety-related information is needed in real time, and when a lack of access to UAS imagery or data could further compromise the immediate safety or security of workers, the public, or critical infrastructure. By separating responsibilities for flight operation, defect identification, and situational awareness, multi-person crew configurations can improve both inspection safety and operational efficiency.

In addition to the operational roles directly involved in UAS bridge inspections, several organizational roles are important for successful implementation and long-term management of a UAS program. These may include UAS program manager, chief pilot, regional UAS manager, and bridge inspection manager. Responsibilities associated with these positions include program management, technical guidance, pilot qualification and training, mission approval, regulatory compliance, resource allocation, and coordination of inspection activities. Additional details regarding these roles are provided in the AASHTO (2025) guidelines.

Although obtaining a Remote Pilot Certificate primarily requires passing the FAA Aeronautical Knowledge Test, which does not include practical flight evaluation, multiple local, state, and federal agencies have proposed additional flight training requirements for remote pilots involved in bridge inspection applications (NASEM, 2024). The initial training requirements and recurrent training requirements, beyond FAA requirements, are summarized in Table 1 (IDOT, 2025; NASEM, 2024). In addition to these requirements, AASHTO (2025) guidelines also propose a detailed training program involving knowledge training and flight maneuver training, with the details summarized in Figure 2. Efforts to develop more standardized training and competency evaluation frameworks for UAS-based bridge inspection are ongoing.

Knowledge training

- Flight request form resources
- Risk assessments
- FAA regulations
- Safety considerations

Flight Maneuvers

- Introduction to controls
- Emergency procedures
- Take-off, T-Pattern, land
- Point of interest
- Flight without GPS signal

Figure 2. Diagram. Summary of AASHTO training guidelines.

Source: AASHTO (2025)

Table 1. Summary of Initial and Recurrent Training Requirements Beyond FAA Requirements

Entity (Year of Publication)	Initial Training Requirement	Recurrent Training Requirement
Illinois DOT (2025)	Ensure the pilot has a current working knowledge of the airspace intended for operations, air traffic control communication requirements, specific UAS aerodynamic factors, and the ability to obtain and interpret weather Demonstrate proficiency to chief remote pilot or UAS program manager	1. Complete 3 operational missions, or complete 1 practice mission to include three (3) takeoffs and landings every 90 days using a department-owned UAS. 2. Demonstrate proficiency to the area UAS chief remote pilot every two years

Entity (Year of Publication)	Initial Training Requirement	Recurrent Training Requirement
Connecticut DOT (2019)	50 flights or 10 flight hours	At least 1 flight per month
Georgia DOT (2017)	At the discretion of the UAS program manager	At the discretion of the UAS program manager
Minnesota DOT (2020)	Oral and practical demonstration	3 flights per quarter
Nevada DOT (2018)	None	1 hour per month
North Carolina DOT (n.d.)	2 flight hours	1 flight within 60 days
Oregon DOT (2018)	6 flights within 90 days at a controlled site	6 flights within 90 days
Tennessee DOT (n.d.)	At the discretion of the remote pilot in command	3 launches and recoveries within 90 days
Texas DOT (2020)	5 flight hours in a rotary-wing UAS, 20 takeoffs in a fixed-wing UAS	3 takeoffs/landings within 1 month
Utah DOT (2017)	2 test flights with the UAS coordinator	None
Virginia DOT (2021)	5 flight hours in a rotary-wing UAS, 20 takeoffs in a fixed-wing UAS	3 takeoffs/landings within 1 month
Washington State DOT (2018)	WSDOT-approved basic flight proficiency test	At the discretion of the UAS coordinator
City of Los Angeles (2017)	5 flight hours	1 flight within 90 days
US Forest Service (2020)	32-hour agency training course	3 takeoffs/landings within 90 days

CHAPTER 3: REVIEW OF CASE STUDIES ON DATA COLLECTION

The application of UAS in bridge inspection can generally be summarized by the workflow presented in Figure 3. The main processes include mission planning, data acquisition, data processing, condition evaluation, results reporting, and data storage and management. The workflow begins with data acquisition, in which UAS equipped with different sensors collect inspection data from target bridge components. The collected data are then processed, either through visual examination and quality control of the imagery or through advanced image processing and 3D modeling and reconstruction techniques, to prepare for further analysis. Subsequently, condition evaluation is performed to identify defects and assess structural conditions. Based on these results, inspection reports are generated to document bridge conditions and maintenance recommendations. Finally, inspection data and reports are archived in data storage and management systems to support long-term monitoring and asset management.

Although the primary focus of this synthesis study is bridge inspection, data collected using UAS can also support a range of engineering and asset management applications beyond condition assessment. High-resolution imagery, georeferenced point clouds, and 3D models generated from UAS surveys provide persistent digital records of bridge geometry and condition that can be used for load rating, bridge management, maintenance decision-making, rehabilitation planning, and construction monitoring. The broader applications of UAS-collected data can increase the overall value of UAS deployment by allowing a single data collection effort to support multiple activities throughout the bridge life cycle.

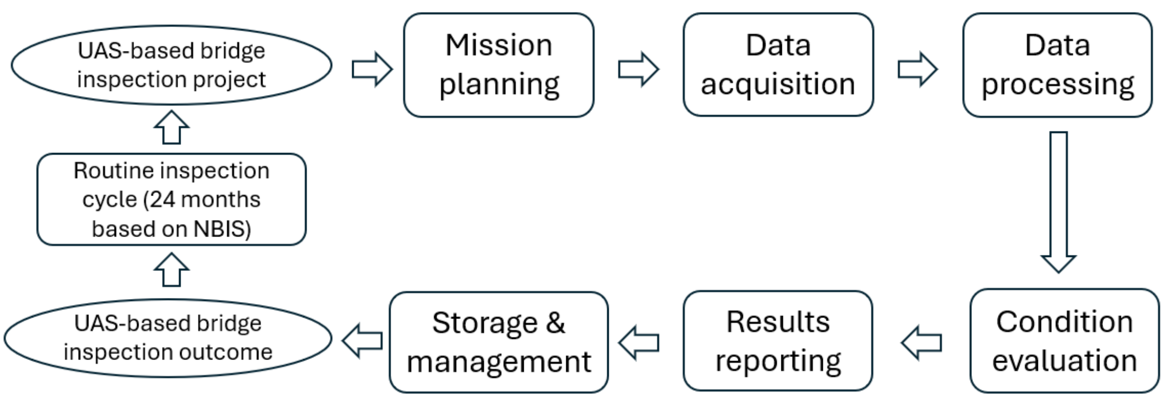


Figure 3. Diagram. UAS-based bridge inspection workflow.

Source: Lin et al. (2021)

Among previous on-site case studies, most efforts have focused primarily on UAS-assisted visual data collection during bridge inspections. Therefore, this chapter summarizes the configurations, approaches, quality assurance considerations, and safety considerations related to visual data collection in existing studies. The comparatively limited efforts related to data processing, analysis, and reporting are discussed in the next chapter.

OVERVIEW OF CASE STUDIES

Previous case studies were reviewed and summarized with respect to the UAS platforms used, inspection types, target bridge types, and operational crew configurations, as presented in Table 2. This table details 12 reports describing pilot case studies from various state and federal agencies, with their geographic distribution illustrated in Figure 4. Based on the findings from these case studies, key considerations were identified and categorized into five areas: inspection type, inspection target, UAS selection, quality assurance, and safety. These considerations are summarized in Figure 5, and the following sections provide a detailed discussion of each consideration and the lessons learned from the reviewed case studies.

Table 2. Summary of Data Collection in Previous Case Studies

Agency	UAS Used	Inspection Type	Bridge Type	Crew
National Cooperative Highway Research Program (NASEM, 2024)	Two UAS (not reported)	Routine inspection	22 bridges of various types	5 members with 3 with pilot certificate
Minnesota Department of Transportation (MnDOT) (Wells and Lovelace, 2021)	Flyability Elios; Intel Falcon 8+; Parrot Anafi	3D reconstruction; routine inspection; fracture-critical inspection	6 bridges, including cable-stayed, concrete box beam, truss, culvert, and masonry arch bridges	2-person crew: engineer-pilot + field engineer
Wisconsin Department of Transportation (WisDOT) (Michael Baker International, 2017)	Falcon 8; DJI Inspire 1	Routine inspection	2 steel deck girder bridges; 1 steel truss bridge	Pilot and inspector dual control
FHWA (Neubauer et al., 2021)	Commercial UAS (not reported)	Routine inspection; proof-of-concept; bridge deck inspection	Steel bridge over river (Maine); steel bridge (Colorado); highway bridge over traffic (Utah)	Pilot and inspector dual control

Agency	UAS Used	Inspection Type	Bridge Type	Crew
Massachusetts Department of Transportation (MassDOT) (Ni and Plotnikov, 2019)	DJI Phantom 4 Pro	Not reported	Steel truss bridge	Minimum 2 crew: pilot + observer
Idaho Transportation Department (ITD) (Dorafshan et al., 2017)	3DR Iris + GoPro; DJI Mavic	Fracture-critical inspection; steel fatigue crack detection	Laboratory bridge; full-scale steel girder bridge	1 licensed pilot
Oregon Department of Transportation (ODOT) (Gillins et al., 2018)	SenseFly Albris; DJI Phantom 3 Pro; DJI S900 + Sony WX500	Mainly routine inspection; one detailed inspection	5 bridges; 3 communication towers	Pilot + visual observer + bridge inspector
Transportation Consortium of South-Central States (Tran-SET) (Darby and Gopu, 2018)	Yuneec H520	Routine inspection	A steel truss bridge	Pilot + inspectors
Florida Department of Transportation (FDOT) (Bridge and Ifju, 2018)	DJI S1000+; custom-built UAS	High mast light poles (HMLP) inspection; special/damage inspection; routine inspection	8 bridges (steel and concrete); 6 high mast light poles	Pilot + visual observer + inspector
Mountain-Plains Consortium (Guo et al., 2021)	DJI Matrice 600 Pro + Zenmuse X3; DJI Phantom 4 Pro V2.0; DJI Mavic 2 Zoom	Not reported	2 concrete bridges with minor damage	Not reported

Agency	UAS Used	Inspection Type	Bridge Type	Crew
Indiana Department of Transportation (INDOT) (Hubbard and Hubbard, 2020)	Not reported	Damage assessment	Bridge impacted by vehicle	UAS team
Michigan Department of Transportation (MDOT) (Brooks et al., 2022)	DJI Phantom 3A + Nikon D810; DJI Mavic 2 Pro; Bergen Hexacopter + FLIR Vue Pro; Skydio	Mainly deck inspection; some structural inspection	6 bridges of various types	Not reported

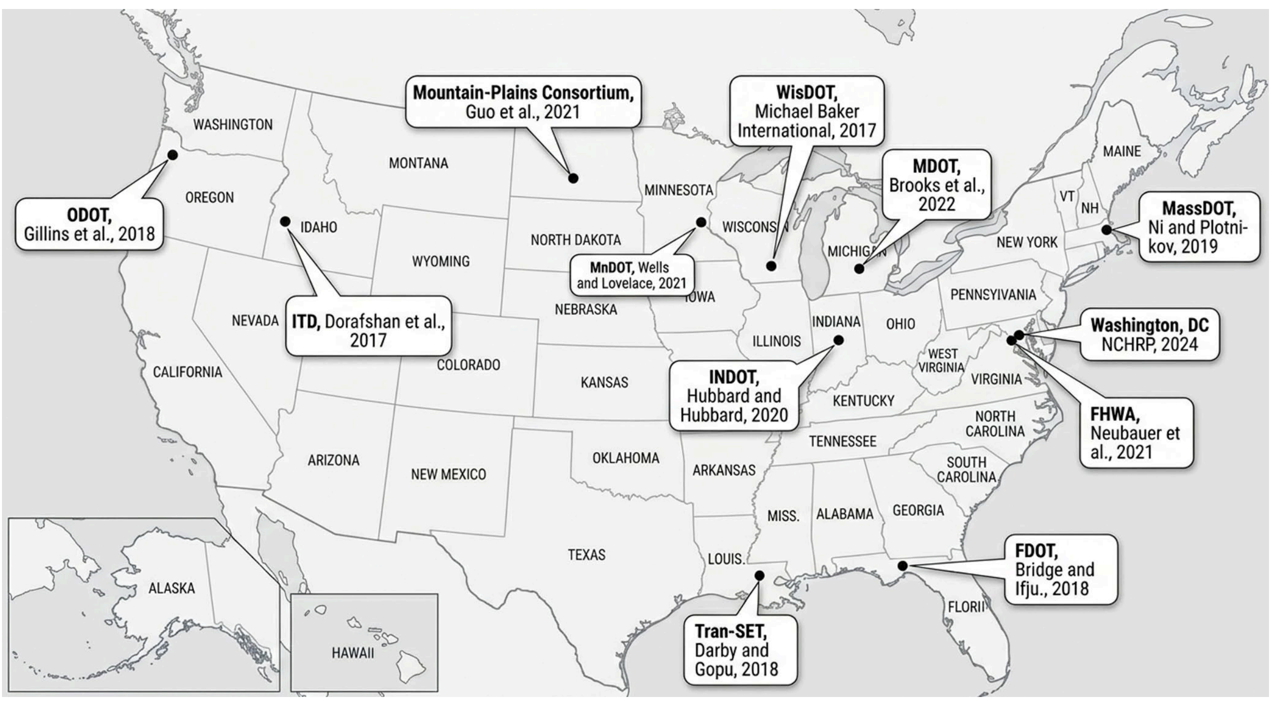


Figure 4. Illustration. Geographic distribution of the reviewed pilot studies by sponsoring agency location.

Source: Authors

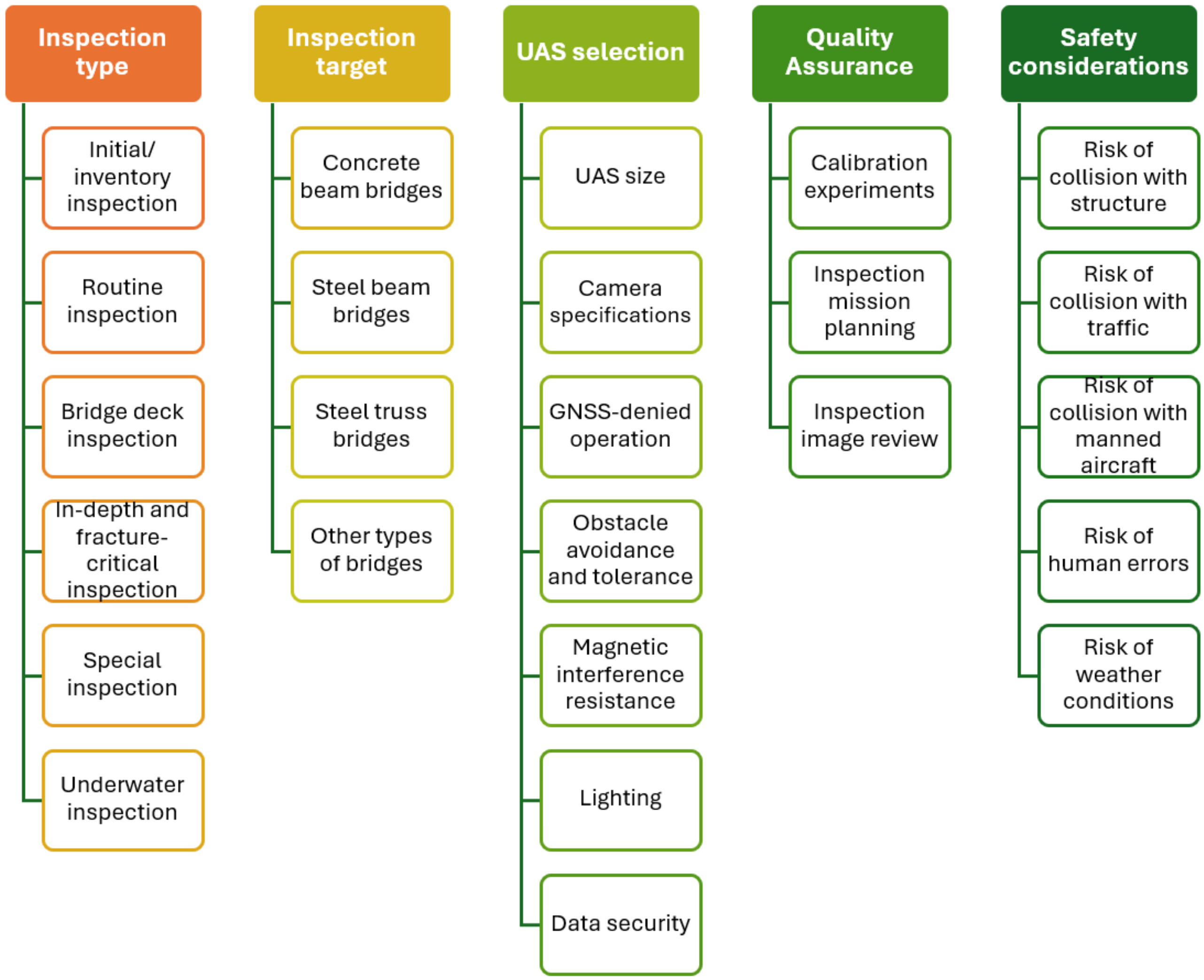


Figure 5. Diagram. Overview of key considerations summarized from the literature review.

Source: Authors

CONSIDERATIONS FOR INSPECTION TYPE

Routine Inspection

Most case studies applied camera-equipped UAS to routine bridge inspection, which primarily relies on visual assessment and does not require hands-on or arm's-length access to structural components unless such access is needed to determine condition. Across these studies, camera-equipped UAS deployment was consistently reported to improve inspection efficiency, accessibility, and operational safety. By enabling remote image collection from difficult-to-access areas such as beneath bridge decks, around tall piers, or above waterways, camera-equipped UAS can reduce the need for costly access equipment, including under-bridge inspection vehicles, scaffolding, and lane closures. In addition, UAS-based inspection reduces inspector exposure to hazardous environments, thereby improving worker safety. Overall, routine inspection appears to be the inspection type that benefits most from camera-equipped UAS deployment.

Bridge Deck Inspection

Bridge deck inspection has also been shown to be well suited to UAS-based inspection (Brooks et al., 2022; Neubauer et al., 2021). In both reports, UAS equipped with thermal cameras were successfully used to detect concrete deck delamination through thermal anomalies. However, the studies also noted that although UAS-based thermal inspection can efficiently identify potential delaminated areas, supplementary methods such as sounding or other nondestructive evaluation techniques are still necessary to verify and quantify the extent of the delamination. Consequently, UAS-based bridge deck inspection is currently more suitable as a rapid screening or localization tool rather than a complete replacement for conventional inspection methods.

Fracture-Critical, Special, and In-Depth Inspections

Some case studies have explored the application of camera-equipped UAS to fracture-critical, special, and in-depth bridge inspections (Wells and Lovelace, 2021; Dorafshan et al., 2017; Bridge and Ifju, 2018). These studies generally concluded that camera-equipped UAS are less suitable for such inspection types because they often require close-up, hands-on evaluation that is difficult to perform remotely. Additionally, Neubauer et al. (2021) reported that the use of camera-equipped UAS for in-depth inspections may result in higher inspection costs, further highlighting the limitations of camera-equipped UAS deployment for these inspection activities. Consequently, camera-equipped UAS are more commonly used as supporting tools to improve accessibility, identify potential defects, or collect imagery for documentation, rather than as direct replacements for conventional inspection methods. Some studies have attempted to develop UAS platforms capable of contact-based inspection (Nguyen et al., 2024; Sanchez-Cuevas et al., 2019), with the goal of enabling physical interaction with structural components for hands-on inspection. An example is presented in Figure 6, in which a UAS is designed to attach to bridge beams and perform close-range inspection. However, such technologies remain at an early stage of development and currently have very limited commercial adoption in practical bridge inspection applications.

Figure 6. Photo. Demonstration of a UAS designed for close-up inspection.

Source: Nguyen et al. (2024)

Underwater Inspection

As aerial robots, UAS are not capable of performing underwater inspections. However, researchers have explored the use of unmanned underwater systems (UUS) for underwater bridge inspection tasks, particularly for evaluating bridge scour and submerged structural components (Kerenyi et al., 2018; Chen et al., 2024). These systems typically use acoustic imaging technologies, such as sonar, to inspect underwater environments where optical imaging is ineffective due to low visibility or water turbidity. Although UUS-based inspection remains less mature than UAS-based inspection, such technologies demonstrate the potential for robotic systems to support bridge inspection in challenging underwater environments.

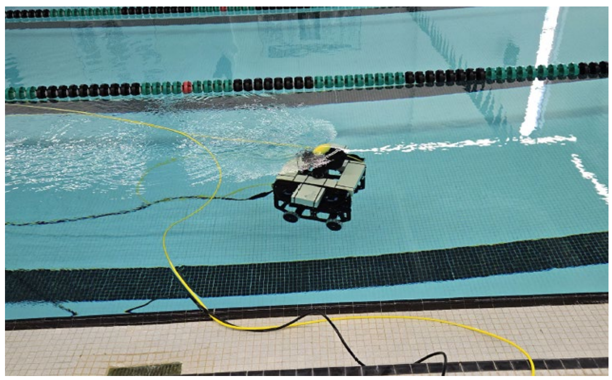


Figure 7. Photo. Demonstration of a UUS tested in a swimming pool.

Source: Chen et al. (2024)

Initial and Inventory Inspection

Although none of the reviewed reports explicitly discussed the application of UAS for initial or inventory inspections, the reality-mapping capabilities of UAS suggest significant potential for these inspection types. Using computer vision-based or LiDAR-based 3D reconstruction, UAS can efficiently collect comprehensive visual and geometric data and generate georeferenced digital records of the structure. These data products can support the development of bridge inventories, facilitate condition documentation, and provide a reference for future inspections, maintenance activities, and asset management.

CONSIDERATIONS FOR INSPECTION TARGET

Previous case studies have applied camera-equipped UAS to a wide variety of bridge types, demonstrating that UAS-based visual inspection can be performed for nearly all bridge categories (NASEM, 2024). However, different bridge types present distinct inspection challenges and may require different UAS configurations, inspection considerations, and operational strategies to achieve effective and reliable inspection outcomes.

Concrete Beam Bridges

Most common defects in concrete beam bridges, including concrete spalling, exposed reinforcement, efflorescence, and staining, can be identified using UAS-collected imagery. In contrast, concrete cracking remains one of the most challenging defect types to detect because its visibility is highly dependent on factors such as standoff distance, viewing angle, camera sensor configuration, and illumination conditions. Multiple studies have suggested that laboratory experiments or controlled field tests are necessary to determine the imaging configurations required to reliably detect cracks above target width thresholds, with further details discussed in the quality assurance section of this chapter.

Steel Beam Bridges

Most common defects in steel beam bridges, including corrosion, coating deterioration, and section loss, can be effectively identified using UAS-collected imagery. In contrast, fatigue cracking is one of the more challenging defect types to detect because of its typically small size and localized occurrence near welds or connections, as reported in Dorafshan et al. (2017). Similar to concrete crack detection, laboratory experiments or controlled field tests are often necessary to determine the imaging configurations required for reliable detection of steel fatigue cracks.

Another challenge associated with steel beam bridges is 3D reconstruction performance. Compared with concrete surfaces, steel members are often smoother, are more reflective, and contain fewer natural visual features, which can hinder feature extraction and matching in computer vision image-based and video-based 3D reconstruction workflows, potentially resulting in incomplete reconstruction, holes, or geometric misalignment in the generated models (Neubauer et al., 2021).

In addition, steel beam bridges may introduce magnetic interference caused by large steel structural elements (NASEM, 2024; Bridge and Ifju, 2018; Michael Baker International, 2017). Such interference can degrade magnetometer measurements and affect heading estimation, potentially reducing flight stability and localization accuracy when operating close to steel members. Consequently, inspections of steel bridges place greater demands on robust GNSS-denied localization and sensor-fusion capabilities.

Steel Truss Bridges

Similar to steel girder bridges, challenges associated with image-based reconstruction and magnetic interference are also present in steel truss bridges due to the abundance of steel members and the complexity of the structural environment (Wells and Lovelace, 2021; Michael Baker International, 2017). In addition, the dense arrangement of interconnected members, gusset plates, and internal components further increases the difficulty of achieving complete inspection coverage and raises collision risk during close-range operations. Therefore, inspection of steel truss bridges requires careful mission planning, and UAS platforms with advanced obstacle avoidance capability, collision tolerance, and resistance to magnetic interference are particularly important for safe navigation and effective inspection performance.

Other Types of Bridges

Case studies involving other bridge types remain relatively limited. Previous studies applied camera-equipped UAS to inspect bridge types, including cable-supported bridges and masonry bridges, and reported reliable and efficient inspection outcomes in both cases (Wells and Lovelace, 2021). These results further demonstrate the potential broad applicability of UAS-based inspection across different bridge types, although bridge-specific challenges and operational considerations may still vary depending on structural characteristics.

CONSIDERATIONS FOR UAS SELECTION

UAS can generally be categorized as fixed-wing or multirotor platforms. Fixed-wing systems offer higher flight speeds but require continuous forward motion and large operating spaces, making them primarily suitable for large-area surveying tasks such as bridge deck inspection (Ni and Plotnikov, 2019). In contrast, multirotor platforms are generally considered more suitable for bridge structural inspection because they can maintain stable hovering at designated viewpoints, perform slow and precise maneuvers near structural components, and provide greater controllability in complex environments. Consequently, multirotor UAS have been widely applied in various bridge inspection tasks, including both deck inspection and detailed structural inspection. Therefore, the following discussion on UAS selection focuses primarily on multirotor platforms.

Although multirotor UAS provide superior maneuverability, most commercial systems are primarily designed for operation in relatively open environments and for capturing downward-facing imagery, where obstacles and targets above the aircraft are limited. In bridge inspection applications, however, UAS are often required to operate in confined spaces beneath bridge decks and capture upward-facing imagery of critical superstructure components. As a result, selecting an appropriate UAS platform is a critical consideration for bridge inspection, as platform capabilities directly affect inspection quality, operational safety, and mission efficiency. Previous reports have emphasized that no single UAS platform is universally optimal for all bridge inspection scenarios (Gillins et al., 2018) and that platform selection should account for multiple operational and environmental factors. These considerations have been discussed across various reports and are summarized below.

UAS Size

UAS size is an important factor influencing payload capacity, wind resistance, maneuverability, and accessibility during bridge inspection. Larger UAS platforms generally provide greater payload capacity, enabling them to carry heavier sensing equipment, and they typically exhibit better resistance to strong winds, which are common around bridge structures. However, larger systems are often more expensive and less accessible in confined environments. In contrast, smaller UAS are generally easier to control in restricted spaces and offer better access to internal bridge components. For example, small platforms can fly between girders to closely inspect girder sides and other confined structural regions, which is both highly important and particularly challenging in bridge inspection applications. Therefore, UAS selection should generally favor the smallest platform capable of carrying the required sensing payload while still maintaining sufficient flight stability and operational safety.

For visual inspection tasks using consumer-grade digital images and videos, small UAS platforms within the 0.55 to 55 lb range defined by FAA Part 107 are most commonly used, with preference typically given to the lower end of this range because of improved maneuverability and accessibility. In some cases, micro-UAS weighing less than 0.55 lb and equipped with lightweight cameras can also be effective for confined-space inspections. For inspections requiring heavier sensing systems, such as infrared thermal cameras or LiDAR sensors, small to medium-sized UAS platforms are generally more suitable because they provide greater payload capacity and flight stability. Applications involving even heavier sensors, such as radar or sonar systems, typically require larger small-category UAS platforms. In current practice, it is very rare to use UAS larger than 55 lb to bridge inspection.

Camera Specifications

Because visual inspection is the most common application of UAS-based bridge inspection, camera and gimbal parameters are important for achieving the desired inspection quality with reasonable efficiency. Most commercial UAS platforms are equipped with integrated optical cameras that can be directly used for bridge inspection image collection. When selecting a UAS platform for inspection applications, several camera parameters should be considered because they directly influence imagery and inspection quality.

Image resolution and focal length are two of the most important camera parameters because they jointly determine the achievable ground or surface sampling distance and field of view. Higher image resolution generally enables finer surface details to be captured, improving the ability to identify small defects. Meanwhile, longer focal lengths or optical zoom capabilities allow inspectors to capture detailed images of structural components from larger standoff distances. However, longer focal lengths reduce the field of view, resulting in smaller scene coverage, lower inspection efficiency, and increased sensitivity to motion blur and vibration. In contrast, shorter focal lengths provide wider coverage and improved image overlap, which are beneficial for efficient inspection. Therefore, UAS platforms with adjustable focal lengths or optical zoom capabilities are generally preferred because they provide flexibility to balance detailed defect inspection with efficient large-area data collection under different inspection scenarios.

In addition to camera configurations, the gimbal's ability to capture upward-facing imagery is an important consideration, since a common bridge inspection scenario involves flying beneath the bridge deck and imaging superstructure components from below. This capability is typically characterized by the maximum upward gimbal pitch angle, and a gimbal capable of rotating 90° upward is generally preferred because it provides greater flexibility for inspecting bridge superstructures and other confined structural regions.

GNSS-Denied Operation

The ability to maintain stable hovering without reliable GNSS signals is a critical requirement for bridge inspection UAS platforms, as mentioned in multiple reports (Neubauer et al., 2021; Dorafshan et al., 2017; Wells and Lovelace, 2021). In many bridge inspection scenarios, especially beneath bridge decks or around dense steel and concrete structures, GNSS signals may become weak, unstable, or completely unavailable due to signal blockage and multipath effects. Under these conditions, the UAS that rely heavily or exclusively on GNSS positioning may experience drift and unstable hovering, which can increase the risk of collisions and crashes.

Therefore, UAS platforms with the ability to hover in GNSS-denied environments are highly preferred for bridge inspection applications. Such capabilities are typically achieved through the integration of onboard sensing and localization technologies, including vision positioning systems based on optical cameras and simultaneous localization and mapping (SLAM) algorithms using sensors such as monocular cameras, stereo cameras, or LiDAR.

However, even with GNSS-denied positioning or localization capabilities, stable hovering above water can still be challenging (Neubauer et al., 2021), as specular water surfaces often provide limited visual features and unreliable depth information for onboard sensing systems. Vision-based positioning methods may suffer degraded performance due to reflections, glare, and the continuously changing appearance of the water surface, while LiDAR sensors may also struggle to obtain reliable measurements. Consequently, for inspections of bridges over water, localization systems that incorporate upward or side-facing sensors are often necessary to maintain stable hovering and ensure safe mission execution.

Obstacle Avoidance and Tolerance

Due to the confined and obstacle-rich environments commonly encountered beneath bridge decks, obstacle avoidance and tolerance have been identified as important requirements in multiple reports (Ni and Plotnikov, 2019; Neubauer et al., 2021; Hubbard and Hubbard, 2020).

Obstacle avoidance capabilities are typically achieved through onboard sensing systems, including optical cameras and LiDAR sensors, which enable the UAS to detect nearby obstacles, estimate surrounding distances, and actively prevent potentially hazardous movements. However, the obstacle avoidance function can also prevent a pilot from flying the UAS into confined spaces, depending on the minimum configurable obstacle-avoidance distance. This is an important consideration when inspections require close-proximity operation within extremely restricted spaces, such as between girders.

In addition to active obstacle avoidance, collision tolerance is also an important consideration for bridge inspection UAS platforms. Collision tolerance is generally achieved through hardware-level protective designs that reduce the likelihood of severe damage during minor impacts. For example, some UAS platforms incorporate propeller guards to prevent fast-rotating propellers from directly contacting hard surfaces, which could otherwise lead to immediate instability or crashes. Other platforms use full protective cages surrounding the entire UAS, providing more comprehensive protection against collisions from multiple directions and enabling safer operation in narrow inspection environments. Examples of such collision-tolerant UAS are presented in Figure 8.

(a) UAS with propeller guards. Source: Autelpilot

(b) UAS with a protective cage. Source: Elios

Figure 8. Photo. Examples of collision-tolerant UAS.

Magnetic Interference Resistance

When flying between or around steel girders, magnetic interference can become a significant challenge for UAS-based bridge inspection. Large steel structural components may distort the local magnetic field and interfere with onboard magnetometers or compasses, potentially causing heading estimation errors, unstable flight behavior, or loss of navigation accuracy. These effects are particularly problematic when the UAS operates in confined spaces close to steel members, where accurate attitude estimation and stable hovering are critical for safe inspection. Multiple reports have mentioned the challenge of magnetic interference that occurred during their on-site application (NASEM, 2024; Bridge and Ifju, 2018). Therefore, resistance to magnetic interference is an important consideration for steel bridge inspections.

To mitigate this issue, UAS platforms with reduced dependence on magnetometer measurements and robust sensor-fusion capabilities are generally preferred. Advanced flight control and localization algorithms can integrate information from inertial measurement units (IMUs), cameras, and LiDAR sensors to maintain stable flight and reliable state estimation even when magnetic measurements become unreliable.

Lighting

Lighting capability is another important consideration for UAS-based bridge inspection because many inspection scenarios involve low-light environments beneath bridge decks or inside box girders, where natural illumination is limited. Insufficient lighting can significantly reduce image quality and make it more difficult to identify defects. In addition, poor illumination may negatively affect visual positioning systems and obstacle avoidance performance, both of which often rely on sufficient visual features for reliable operation.

Therefore, UAS platforms used for bridge inspection should either include integrated lighting systems or provide sufficient payload capacity, power supply capacity, and mounting interfaces for external lighting equipment. Adjustable and directional lighting is particularly beneficial because it improves surface visibility, reduces shadows, and enhances inspection effectiveness when operating around complex structural geometries and confined regions.

Data Security

Data security and information protection are increasingly important considerations in UAS-based bridge inspection, particularly because inspection operations often involve the collection of high-resolution imagery, geospatial data, and critical infrastructure information. Therefore, when selecting UAS platforms for bridge inspection, cybersecurity-related factors, including onboard data storage, encrypted communication, cloud connectivity policies, and component sourcing, should be considered to ensure secure data management and operation.

Several transportation agencies and federal organizations have emphasized the use of secure and trusted UAS platforms for infrastructure inspection applications. One important recent development is the establishment of NDAA-compliant UAS requirements associated with the US Department of Defense (National Defense Authorization Act for Fiscal Year 2020, 2019). NDAA compliance generally refers to UAS platforms that satisfy restrictions defined in the National Defense Authorization Act, particularly regarding the use of certain foreign-manufactured components and communication systems in federal and federally funded applications. These requirements aim to reduce cybersecurity and supply-chain risks in sensitive government and critical infrastructure operations. In 2024, the US Congress further expanded these restrictions by prohibiting federal procurement, operation, and federally funded use of covered foreign UAS platforms and components (National Defense Authorization Act for Fiscal Year 2024, 2023).

Another related initiative is the “Blue UAS” program (commonly referred to as the Blue List), established by the Defense Innovation Unit (DIU) to identify UAS platforms that satisfy cybersecurity, supply-chain, and operational security requirements for government use (Defense Innovation Unit, n.d.). While NDAA compliance primarily focuses on restrictions related to component sourcing and foreign-manufactured technologies, Blue UAS certification involves additional evaluation of data handling, firmware security, communication protocols, operational reliability, and supply-chain integrity. As a result, UAS platforms included in the Blue UAS list are generally considered more suitable for sensitive infrastructure inspection tasks.

In addition, the “Green UAS” program, developed by the Association for Uncrewed Vehicle Systems International (AUVSI), provides a commercial-oriented certification framework aligned with Blue UAS cybersecurity principles for non-defense applications such as transportation, utilities, public safety, and infrastructure inspection (AUVSI, n.d.). DIU has recognized Green UAS certification as an authorized pathway for achieving Blue UAS-cleared status (AUVSI, 2025).

Together, NDAA-compliant UAS requirements, the Blue UAS list, and the Green UAS certification framework provide important references for evaluating data security considerations in UAS platform selection. Consequently, the rapidly evolving nature of these regulations and compliance requirements requires continuous monitoring to ensure the most up-to-date standards are used when launching new UAS inspection initiatives.

CONSIDERATIONS FOR QUALITY ASSURANCE

One important aspect of UAS-based bridge inspection is quality assurance, which aims to ensure that areas of interest are comprehensively covered and that collected imagery is of sufficient quality for identifying potential defects. In practice, three common approaches are used: controlled experiments to determine suitable imaging configurations, inspection mission planning, and inspection image quality review.

Calibration Experiments for Visual Inspection

As discussed previously, cracks are among the most challenging defects to detect because of their small size, creating the need to carefully control visual inspection parameters such as standoff distance, viewing angle, and illumination conditions. Moreover, the optimal values of these parameters vary depending on camera specifications and the target crack width being detected. Consequently, multiple reports have recommended laboratory experiments or controlled field tests to establish parameter thresholds required to ensure adequate image quality for defect detection (NASEM, 2024; Neubauer et al., 2021; Dorafshan et al., 2017; Bridge and Ifju, 2018; Wells and Lovelace, 2021).

In the MnDOT case study (Wells and Lovelace, 2021) researchers conducted a comprehensive study in which three different camera-equipped UAS platforms were used to capture images of a test target at distances ranging from 10 ft to 100 ft. Based on the collected images, the minimum distinguishable line width was determined for each camera at each distance, providing guidance for selecting appropriate standoff distances under different inspection requirements, as presented in Figure 9. Similar experiments were performed to evaluate the influence of viewing angle on crack detectability. As expected, shorter standoff distances and viewing angles closer to normal incidence generally improve the ability to detect smaller cracks. Such experiments should preferably be conducted with the UAS in flight rather than stationary on the ground because motion-induced image blur may significantly affect image quality and defect detectability.

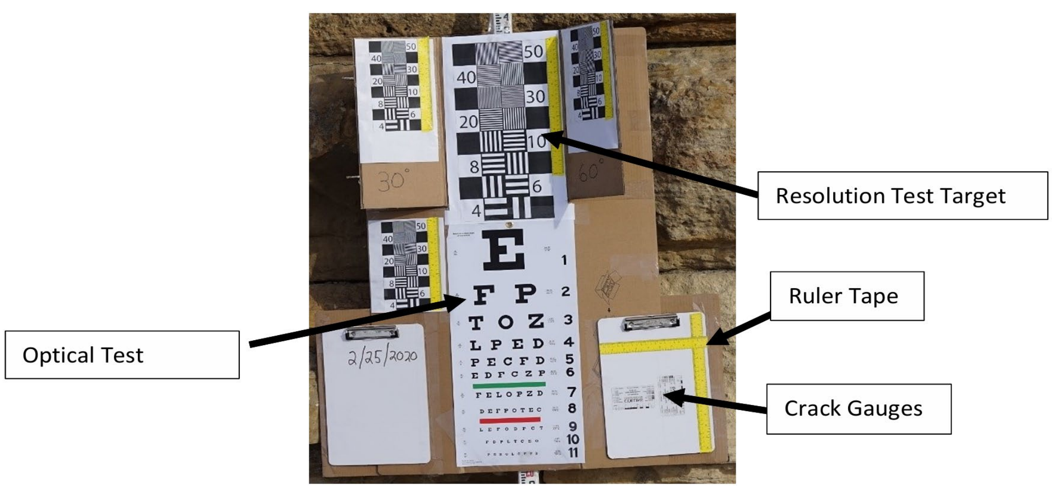


Figure 9. Photo. Experimental setup for visual inspection configuration evaluation.

Source: Wells and Lovelace (2021)

Regarding the target crack width for detection, different studies have used different thresholds. A useful reference is provided by the *Manual for Bridge Element Inspection* (AASHTO, 2019), which considers cracks smaller than 0.012 in. in reinforced concrete and 0.004 in. in prestressed concrete to be insignificant. Therefore, cracks exceeding these thresholds should generally be considered detection targets in inspection imagery. Based on these requirements, the AASHTO (2025) UAS guidelines provide example maximum standoff distances for several UAS and camera configurations and target structure types, ranging from 5 ft to 20 ft. Although these values offer a general reference for mission planning, the guidelines emphasize that the achievable detection capability and allowable standoff distance depend on specific UAS and camera setups.

An alternative approach for estimating suitable inspection configurations is a theoretical calculation based on camera geometry (Ibrahim et al., 2022a). According to the pinhole camera model, the surface sampling distance (SSD) can be estimated using the equation presented in Figure 10.

$$SSD = \frac{D * p}{f} = \frac{2 * D * tan(FOV)}{N}$$

Figure 10. Equation. Calculation of surface sampling distance.

Source: Authors

where *SSD* denotes surface sampling distance, *D* denotes standoff distance, p denotes pixel size, f denotes focal length, *FOV* denotes field of view, and *N* denotes the number of pixels along the corresponding image dimension. The surface sampling distance provides an approximate indicator of the minimum detectable defect size and can therefore serve as a preliminary estimate for determining inspection standoff distances. However, the actual detectable crack width is also influenced by additional factors, including viewing angle, illumination conditions, image compression, and motion blur. Consequently, theoretical calculations should ideally be supplemented by experimental validation under realistic inspection conditions.

Inspection Mission Planning

Mission planning is another important component of quality assurance in UAS-based bridge inspection because it helps ensure that all areas of interest are systematically captured with appropriate standoff distances, viewing angles, and image overlap, reducing the risk of incomplete coverage or insufficient image quality for defect detection. Effective mission planning can also improve inspection efficiency and operational safety by accounting for environmental constraints and bridge geometry.

Previous practices primarily relied on pilot experience and manual planning. Several reports (NASEM, 2024; Dorafshan et al., 2017) suggested that previous inspection records can be used to assess bridge condition and develop more targeted mission plans focused on areas with higher deterioration risk. Some case studies (Guo et al., 2021; Wells and Lovelace, 2021; Gillins et al., 2018) used waypoint-based autonomous flight modes to perform automated inspections of bridge decks, as presented in Figure 11, reducing pilot workload and improving inspection consistency and repeatability. However, inspection of bridge superstructures and substructures, which are typically considered more structurally significant, still relied mainly on manual flight planning because degraded GNSS signals beneath bridge decks make automated navigation challenging. Although some studies have explored automated inspection approaches in GNSS-denied environments (Brooks et al., 2022), practical applications remain in their early stages.

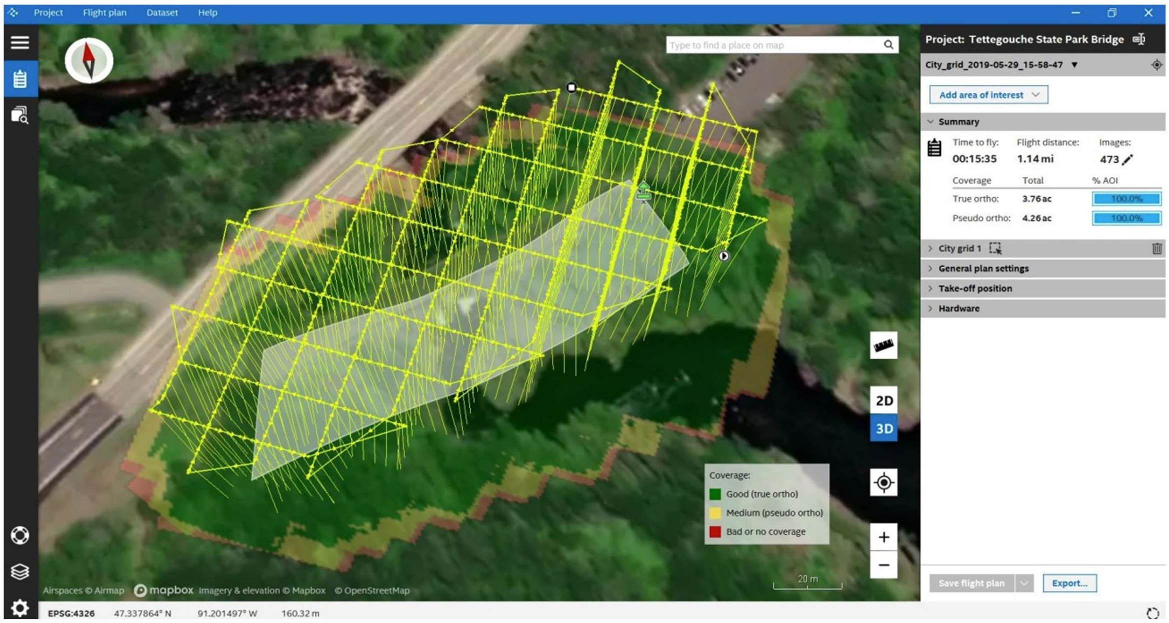


Figure 11. Screenshot. Waypoint-based autonomous flight mission plan.

Source: Wells and Lovelace (2021)

Inspection Image Review

Multiple reports emphasized that real-time review is an important approach for ensuring image coverage and image quality, both of which are critical to the reliability of UAS-based bridge inspection. In several case studies (Gillins et al., 2018; Bridge and Ifju, 2018), on-site bridge inspectors were responsible for reviewing the first-person-view video or image stream captured by the camera-equipped UAS in real-time and communicating with the pilot to adjust the UAS position and camera orientation toward areas of interest. Such on-site review enables immediate corrective actions, such as capturing additional images of uncovered regions or moving closer to structural components when image quality is insufficient. This helps reduce the risk of discovering incomplete coverage or inadequate imagery only after returning to the office, which could otherwise require costly return visits for supplemental data collection.

In other studies (NASEM, 2024; Neubauer et al., 2021), additional remote desktop reviews were conducted after or during inspections. These reviews can be performed by team leaders or senior inspectors located in the office, allowing inspection quality to be evaluated efficiently without requiring all personnel to be present on-site. However, remote desktop review also has limitations, particularly due to the difficulty of accurately determining the spatial location and context of captured images, as well as the inability to immediately perform follow-up inspections or collect supplementary imagery when issues are identified.

SAFETY CONSIDERATIONS

Although the application of UAS improves inspection safety by reducing the inspector's exposure to hazardous environments, it also introduces new safety challenges. Some reports (NASEM, 2024; Gillins et al., 2018; Darby and Gopu, 2018; Wells and Lovelace, 2021) have developed safety plans for UAS-based bridge inspection. The safety considerations are summarized below. It is important to note that the likelihood of serious incidents is generally low, particularly for events involving collisions with traffic or manned aircraft. These risks can be further mitigated with mature and reliable UAS platforms, appropriate operator training, careful mission planning, and well-established standard operating procedures.

Risk of Collision with Structures

The risk of collision with bridge structures is one of the most significant safety challenges in UAS-based bridge inspection because inspections often require close-range operation in confined spaces. Such environments may contain complex geometries, occlusions, and degraded GNSS signals, increasing the difficulty of maintaining stable flight and accurate positioning. Collision with structural components can damage the UAS, interrupt inspection operations, or potentially cause secondary hazards if the UAS falls onto traffic or surrounding areas.

To mitigate these risks, several measures have been recommended, including maintaining conservative flight speeds and adequate standoff distances, employing visual observers to enhance situational awareness, and using obstacle avoidance systems and collision-tolerant designs, such as UAS with protective cages or propeller guards, when available. In addition, proper pilot training, preflight planning, and familiarization with complex bridge geometries are important for reducing collision risk and improving operational reliability.

Risk of Collision with Traffic

The risk of collision with moving vehicles is an important safety consideration for UAS-based bridge inspection because inspections are frequently conducted near active roadways. The primary concern is unexpected UAS malfunction, loss of control, battery failure, or collision with bridge structures, which could result in the UAS falling onto traffic and causing secondary accidents. To mitigate these risks, several measures have been recommended, including limiting the size and weight of the UAS to reduce potential impact severity, avoiding sustained flight directly above moving vehicles whenever possible, and selecting reliable UAS platforms with proven operational performance and safety features. In addition, temporary traffic control measures, lane closures, and predefined emergency procedures can further reduce risks associated with equipment failure or unexpected flight behavior.

Risk of Collision with Manned Aircraft

Bridge inspection operations generally involve a relatively low risk of collision with manned aircraft because UAS are typically operated close to bridge structures, at low altitudes, and within localized inspection areas. The primary risk arises from unexpected events such as loss of control, communication failure, GNSS malfunction, or flyaway incidents that may cause the UAS to leave the intended operational area. To mitigate these risks, safety plans commonly recommend conducting airspace assessments before flight, maintaining visual line of sight when required, establishing geofencing or flight boundaries, and defining emergency procedures for communication loss or abnormal UAS behavior.

Risk of Human Error

Because of the complexity of UAS operations, pilot error can occur not only during flight maneuvering but also through oversights in important procedures, such as failing to check battery status, sensor calibration, communication links, airspace restrictions, or environmental conditions before flight. Such oversights may increase the risk of equipment failure, loss of control, or UAS crashes during inspection missions. To mitigate these risks, multiple reports have emphasized the importance of following standardized preflight, in-flight, and postflight checklists for every operation. Systematically reviewing checklists helps ensure that critical procedures are completed consistently, reduces the likelihood of human error, and improves operational reliability.

Risk of Weather Conditions

Weather conditions are an important safety consideration for UAS-based bridge inspection because they can significantly affect flight stability, sensor performance, and inspection quality. In Illinois, this concern is especially relevant because many bridges are located in open, exposed, or riverine environments where wind can vary rapidly and create challenging flight conditions. Strong wind is therefore one of the primary concerns, particularly around bridges where airflow may become turbulent because of interactions with structural components and surrounding terrain. Excessive wind can reduce flight stability and increase the risk of collision with structures or loss of control. Rain, snow, and high humidity may damage electronic components or degrade sensor performance, while low temperatures can reduce battery efficiency and shorten flight duration.

In addition, weather conditions directly influence inspection quality. For example, poor illumination can reduce defect visibility in digital imagery, while thermal imaging performance depends strongly on solar radiation and environmental temperature conditions. To mitigate these risks, previous reports have recommended evaluating weather forecasts before operation, establishing environmental thresholds for safe flight, and postponing inspections under unfavorable conditions.

CHAPTER 4: DATA PROCESSING AND REPORTING

Although previous reports have primarily focused on data collection, several case studies have discussed data processing, interpretation, and reporting. These downstream steps are important because the value of UAS-based inspection ultimately depends not only on efficient data acquisition but also on the ability to transform collected data into reliable condition assessments and actionable inspection outcomes. Existing efforts related to data processing and reporting are summarized in this chapter.

DATA TYPES

UAS can carry different sensors to collect various types of data. The commonly collected data in the reviewed case studies are summarized below.

Consumer-Grade Digital Images and Videos

Consumer-grade digital images and videos are the most common forms of data collected by camera-equipped UAS in previous bridge inspection studies. They are primarily used for visual inspection, enabling inspectors to identify visible defects and evaluate structural condition. In addition to direct visual assessment, consumer-grade digital images can also serve as input for image-based 3D reconstruction methods, including structure-from-motion (SfM) and Multi-View Stereo (MVS), to generate dense point clouds, textured meshes, or digital twins of bridge structures. Videos are commonly used for real-time inspection support and documentation, whereas still images are preferred for detailed defect assessment due to their higher resolution and reduced motion blur.

Thermal Image

Thermal images are captured using infrared cameras and record temperature distributions across structural surfaces. Previous studies (Brooks et al., 2022; Neubauer et al., 2021) have demonstrated their applicability for bridge deck delamination detection, where subsurface defects produce thermal anomalies due to differences in heat transfer behavior. Compared with consumer-grade digital imagery, thermal imaging enables identification of defects that may not be directly visible on the surface. However, thermal inspection performance is highly dependent on environmental conditions, including solar radiation, ambient temperature, and data collection time. To maximize thermal contrast between defective and undamaged areas, thermal images are generally recommended for collection during periods of significant heating or cooling, such as early morning or late afternoon, under weather conditions with sufficient sunlight exposure before the inspection.

Point Cloud

Point cloud data, which consist of dense sets of 3D points representing the surfaces of physical objects or environments, can be collected directly using LiDAR sensors or generated indirectly through image-based and video-based 3D reconstruction using consumer-grade digital cameras. Point clouds provide geometric information about bridge structures and are useful for applications such as defect dimension measurement, component dimension measurement, deformation monitoring, and generation of bridge information models (BrIM). Compared with image-based methods, LiDAR can provide more robust geometric measurements in low-texture or low-illumination environments, although the resulting data often require additional processing and registration.

To generate accurately georeferenced LiDAR point clouds, precise positioning information is often important, and real-time kinematic (RTK) or post-processed kinematic (PPK) GNSS is commonly used to improve absolute accuracy and facilitate registration to real-world coordinates. However, high-quality local geometry can also be obtained using alternative positioning methods such as simultaneous localization and mapping (SLAM). In contrast, computer vision image-based and video-based 3D reconstruction methods can estimate relative camera poses and reconstruct 3D geometry without relying on positioning data. Without external references, however, the resulting reconstruction has an arbitrary scale and is not georeferenced. Absolute scale and georeferencing can be established by incorporating positioning information, using ground control points (GCPs), or applying known geometric dimensions as scale constraints.

DATA PROCESSING AND ANALYSIS METHODS

Manual Review

Currently, data processing in UAS-based bridge inspection still relies primarily on on-site and off-site manual review by inspectors. In this workflow, collected images, videos, thermal data, and reconstructed 3D models are examined by experienced inspectors to identify defects, assess structural conditions, and determine the need for further inspection. Manual review remains the dominant approach because bridge inspection often requires engineering judgment, contextual understanding, and interpretation of complex defect patterns that are difficult to fully automate. However, increasing efforts have been devoted to partially automating and improving data processing and analysis, as summarized below.

Computer Vision Image-Based and Video-Based 3D Reconstruction

Computer vision image-based and video-based 3D reconstruction has become an increasingly important application of UAS-based bridge inspection because it enables the generation of dense point clouds, textured meshes, and digital twins from collected consumer-grade digital images. A variety of commercial and open-source software packages have been developed to support these workflows, such as Agisoft Metashape (Agisoft, 2024), Pix4D (Pix4D SA, 2025), RealityCapture (Epic Games, Inc., 2025), and COLMAP (Schönberger, 2025).

Compared with conventional image-based inspection, 3D reconstruction provides additional geometric information, allowing inspectors to perform dimensional measurements, conduct virtual inspection, document defects, and support long-term condition monitoring. High-fidelity 3D models can also support BrIM generation, virtual inspection, and integration with digital asset management systems.

However, achieving accurate and complete reconstruction requires higher-quality image acquisition and more systematic mission planning than conventional visual inspection, as the reconstruction quality depends not only on image resolution but also on image overlap, viewpoint distribution, and scene texture. Sufficient forward and side overlap is necessary to ensure robust feature matching between images, while diverse viewing angles help improve geometric completeness and reduce the effects of occlusions. Guidelines for UAS-based 3D reconstruction are presented in Figure 12.

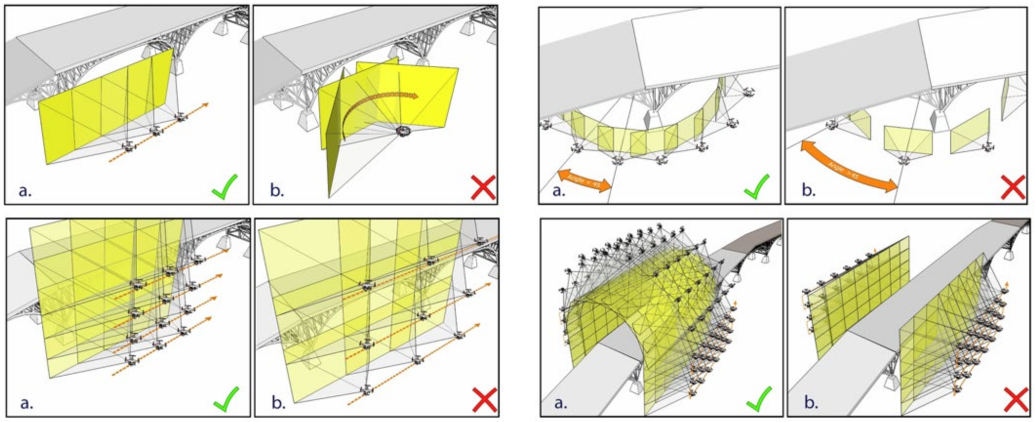


Figure 12. Diagram. Guidelines for image acquisition in computer vision image-based and video-based 3D reconstruction using UAS.

Source: Reconstruct (2017)

Virtual Inspection with 3D Models

With a high-fidelity 3D model of the target structure, previous case studies have conducted virtual inspections in an office environment (Wells and Lovelace, 2021; Michael Baker International, 2017; Guo et al., 2021). Such inspections can be conducted using low-cost screen-based navigation interfaces or more immersive extended reality (XR) frameworks. Figure 13 illustrates a screen-based virtual inspection in which inspectors measure angles between truss members within the reconstructed point cloud and compare the results with design drawings. Figure 14 demonstrates an XR-based virtual inspection platform, enabling inspectors to interact with reconstructed bridge models in a more intuitive and immersive manner.

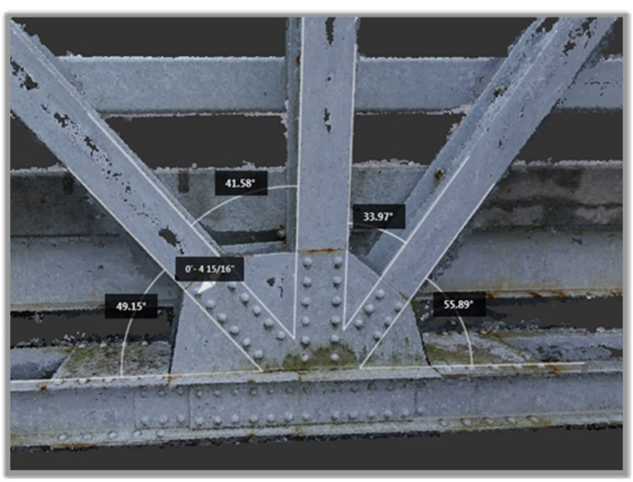


Figure 13. Screenshot. Example application of screen-based virtual inspection.

Source: Michael Baker International (2017)

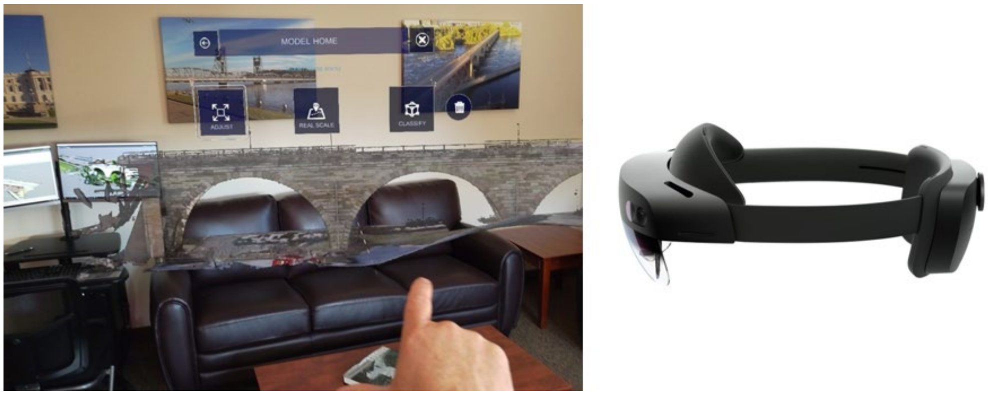


Figure 14. Screenshot. Example application of XR-based virtual inspection.

Source: Wells and Lovelace (2021)

In addition to performing measurements directly on 3D models, an alternative approach involves projecting images onto the reconstructed 3D model and conducting measurements within the 2D image domain. By establishing spatial correspondence between the 3D model and the original images, the physical scale associated with image-based measurements can be determined, enabling quantitative measurements directly from images. This approach can be advantageous because images often preserve finer visual details and provide higher local resolution than the reconstructed geometry. Evidence has shown that image-based measurements integrated with 3D spatial information can improve measurement accuracy compared with measurements performed solely on the reconstructed 3D model (Hoiem, 2018).

Compared with on-site review, virtual inspection allows inspectors to spend more time performing detailed assessments without the time constraints associated with field operations. Compared with image-based off-site review, virtual inspection provides improved spatial understanding of structural components and enables geometric measurements, such as defect dimensions or component sizes, directly within the reconstructed model. As a result, virtual inspection has the potential to improve inspection efficiency, documentation, and the comprehensiveness of structural assessment.

AI-Assisted Image-Based Damage Detection

With the development of computer vision and deep learning, AI-assisted damage detection has been increasingly explored in UAS-based bridge inspection applications (Wells and Lovelace, 2021; Dorafshan et al., 2017; Guo et al., 2021). These approaches aim to automatically identify, localize, and classify structural defects in collected images, thereby reducing the workload associated with manual review and improving processing efficiency.

Before the widespread adoption of deep learning, traditional computer vision methods were widely applied for defect detection. These approaches typically rely on manually designed image-processing algorithms, including edge detection, thresholding, and pattern recognition techniques, to identify potential defects. Traditional methods generally require smaller training datasets and fewer computational resources than deep learning approaches, making them attractive for specific defect types with relatively simple patterns, such as cracks. However, their performance is often sensitive to variations in illumination, viewing angle, image quality, and environmental conditions, limiting their robustness in complex real-world bridge inspection scenarios.

Deep learning-based methods, particularly convolutional neural networks (CNNs) and recent transformer-based models, have been more widely applied to analyze consumer-grade digital images collected by camera-equipped UAS. Three common categories of methods—image classification, object detection, and semantic segmentation—are presented in Figure 15. Image classification aims to determine whether a defect exists within an image and is typically applied to cropped sub-images extracted from larger inspection images. Object detection identifies both the location and category of defects using bounding boxes. Unlike image classification, object detection can produce multiple bounding boxes corresponding to different defect types within a single image. Semantic segmentation provides pixel-level classification, enabling more detailed characterization of defect shapes and extents. Compared with traditional computer vision approaches, deep learning methods generally demonstrate improved robustness to complex backgrounds and environmental variations, making them more suitable for practical bridge inspection scenarios.

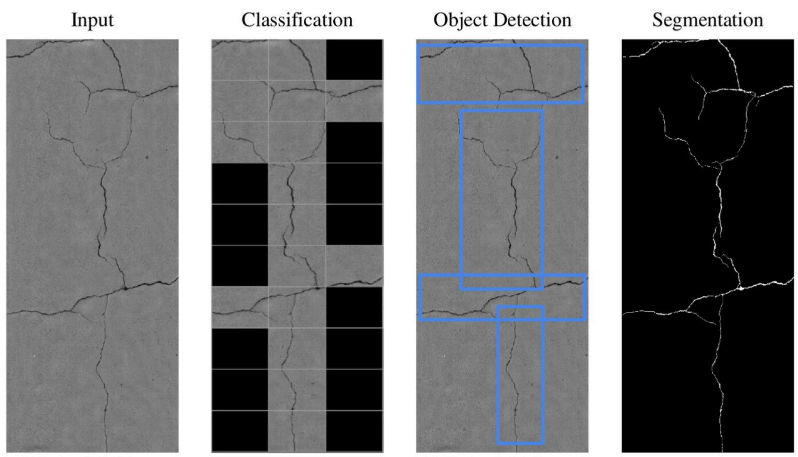


Figure 15. Illustration. Examples of deep learning-based damage detection results, including image classification, object detection, and semantic segmentation.

Source: Hsieh and Tsai (2020)

Although AI-assisted methods have shown promise for improving inspection efficiency and consistency, they currently serve primarily as decision-support tools to assist inspectors rather than replace the entire analysis process. Human interpretation and engineering judgment remain necessary to verify detected defects, assess their structural significance, and draw final inspection conclusions.

AI-Assisted Thermal Image Processing

AI methods have also been explored for processing thermal images. For example, Brooks et al. (2022) applied thermal anomaly and delamination detection (TADDA) algorithm to process thermal images and detect the progression of bridge deck delamination, as presented in Figure 16. The algorithm analyzes thermal patterns and anomalies associated with subsurface defects, enabling more efficient localization and assessment of delaminated areas. This example demonstrates the potential of combining thermal imaging with AI-based processing methods to improve the efficiency and consistency of bridge deck inspection.

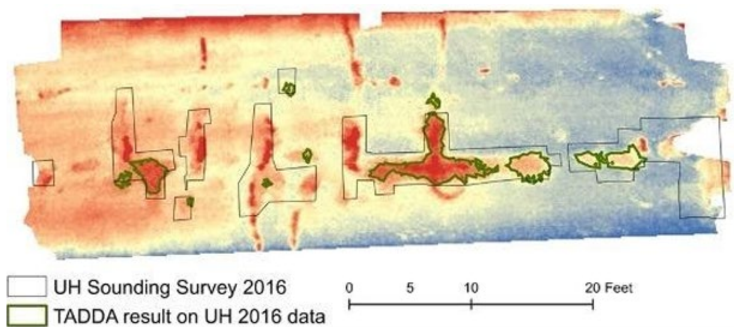


Figure 16. Illustration. Thermal anomaly detection results and comparison with the traditional sounding method.

Source: Brooks et al. (2022)

AI-Assisted Point Cloud Processing

One case study (Guo et al., 2021) applied AI-based point cloud segmentation algorithms to classify different structural components within bridge point cloud data, as presented in Figure 17. With the resulting segmentation information, bridge information models (BrIM) can be generated from the point clouds to support further defect documentation, condition assessment, and reporting. This case study demonstrates the potential of combining AI methods with geometric data processing to improve automation in bridge inspection workflows and facilitate more structured digital asset management.

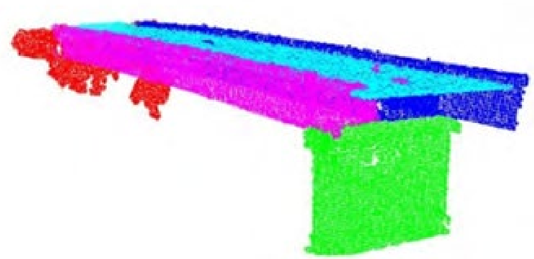


Figure 17. Illustration. Results of bridge point cloud segmentation using a point cloud segmentation algorithm.

Source: Guo et al. (2021)

Reporting

In previous case studies, report-generation workflows primarily relied on inspectors manually selecting representative images from UAS-collected imagery or videos and incorporating them into inspection reports along with defect descriptions, measurements, and condition assessments.

Although this workflow benefits from engineering judgment and flexibility, it can be time-consuming and labor-intensive. However, recent years have seen increasing exploration of automated reporting methods aimed at streamlining defect localization and documentation, integrating inspection results with digital models, and improving reporting efficiency and consistency. Digital twin and model-based reporting approaches provide opportunities to communicate inspection results more intuitively than conventional reports. Inspection findings can be spatially linked to their corresponding bridge components and locations within a 3D model, allowing users to navigate the structure and directly access associated photographs, defect annotations, measurements, condition ratings, and other inspection information. Rather than relying on inspectors or asset managers to interpret textual descriptions of defect locations, such as girder numbers, span numbers, and distances from reference points, a digital model can provide direct spatial visualization of where each defect occurs. These advancements are further summarized in Chapter 6.

CHAPTER 5: ADVANTAGES AND CHALLENGES

ADVANTAGES

Many reports have identified advantages of UAS-based bridge inspection, including improvements in efficiency, cost, quality, and safety, as summarized in this section.

Inspection Efficiency

Most reports have compared the efficiency of UAS-based inspection with that of conventional methods, particularly under-bridge inspection trucks (UBITs). A common conclusion is that UAS-based inspection generally offers higher efficiency than UBITs by reducing setup time, minimizing traffic disruption, and improving accessibility to difficult-to-reach areas. However, an exception was reported by FHWA (2022), in which the application of camera-equipped UAS to in-depth inspection resulted in higher costs than UBIT-based inspection. This suggests that selecting appropriate inspection types is important for fully realizing the efficiency advantages of UAS and that camera-equipped UAS may be more suitable for routine inspection and rapid assessment than for inspection tasks requiring hands-on evaluation.

Another observation reported by NASEM (2024) is that UAS-based inspection may exhibit lower efficiency than conventional ground visual inspection, which typically requires minimal preparation and equipment deployment. Therefore, although camera-equipped UAS can improve efficiency compared with access-intensive methods such as UBITs, their advantages may be limited for bridges with easy access, where conventional inspection methods can be performed more efficiently. For bridges without highly challenging access conditions, such as very high elevations or inaccessible underside components, complementary technologies may provide a more practical alternative. For example, 360-degree cameras mounted on handheld poles can enable inspectors to rapidly and efficiently capture visual data while walking around accessible bridge areas. This technology has not been extensively explored in the reviewed case studies but is discussed further in a later section. Overall, this suggests that the benefits of camera-equipped UAS deployment are highly dependent on bridge accessibility and inspection complexity and that careful selection of inspection scenarios is important to maximize the value of UAS-based inspection.

Inspection Cost

Because equipment and labor costs are strongly associated with the time required to complete inspections, previous studies generally concluded that UAS-based inspection has lower costs than UBIT-based inspection. A summary of reported benefit–cost ratios and cost comparisons is provided in Table 3. Similar to the efficiency findings, an exception was reported (Neubauer et al., 2021), in which the application of camera-equipped UAS to in-depth inspection resulted in higher costs than UBIT-based inspection. In addition, UAS-based inspection can be more expensive than conventional ground visual inspection (NASEM, 2024).

Table 3. Summary of Benefit–Cost Ratios for UAS-Based Inspection

Agency	Findings about Benefit–Cost Ratio (B/C)
ODOT (Gillins et al., 2018)	10% reduction in personnel time; ~$10,200 savings per project; B/C = 9.3
MnDOT	66.02% cost reduction compared with UBIT inspection
INDOT	B/C = 1.1 considering safety improvements and reduced traffic delays (equipment savings excluded)
FDOT	Average cost: $4,810/bridge (UBIT) vs. $4,410/bridge (UAS)

It is also worth noting that, although many benefit–cost analyses assume the addition of a dedicated UAS pilot to the inspection team, bridge inspection engineers often have the aptitude and technical background needed to obtain appropriate training and serve as UAS pilots themselves. Having inspection engineers serve as pilots could further reduce personnel costs while also improving coordination between flight operations and inspection objectives. In addition, providing inspectors with opportunities to operate and apply emerging UAS technologies may enhance job satisfaction and help attract and retain younger bridge inspection professionals.

Beyond time savings, UAS equipment is generally less expensive than UBITs, further contributing to lower inspection costs. Another important advantage is that UAS-based inspection of structural components often does not require lane closures or major traffic control measures, particularly when inspections are conducted beneath a bridge. This can substantially reduce indirect costs associated with traffic disruption, congestion, and inspection-related impacts on bridge users. Therefore, the cost benefits of UAS extend beyond direct operational expenses and also include reductions in societal and transportation-related costs.

Inspection Quality

The quality of UAS-based inspection depends heavily on the target structure, mission planning, and camera and UAS configurations. Most reports concluded that the image quality achieved by camera-equipped UAS is generally sufficient for visual assessment tasks and comparable to that achieved using conventional inspection methods. Another commonly reported advantage is the improved accessibility provided by camera-equipped UAS, which enable inspectors to examine structural surfaces that are difficult or unsafe to access using traditional methods.

However, several exceptions have also been reported. FHWA (Neubauer et al., 2021) reported that it was difficult to achieve the desired inspection quality due to challenging environmental conditions, including strong winds, degraded GNSS signals, and poor illumination. In addition, ITD (Dorafshan et al., 2017) reported that the image quality captured by camera-equipped UAS was insufficient for reliably detecting thin fatigue cracks on steel members. These experiences demonstrate that achieving high inspection quality is not guaranteed by camera-equipped UAS deployment alone and depends strongly on appropriate sensor selection, imaging configurations, environmental conditions, and operational planning. They also highlight the importance of quality assurance procedures to ensure that collected data satisfy inspection requirements.

Inspection Safety

It is widely agreed that the application of UAS can improve inspector safety by reducing the need to work in hazardous environments, such as at height, beneath bridge decks, above waterways, or near active traffic. By enabling remote data collection, UAS can minimize inspector exposure to risks associated with conventional access methods. It is also commonly reported that the use of UAS may improve public safety by reducing or eliminating the need for lane closures and traffic disruptions during inspection, thereby lowering risks to road users.

Another advantage reported by FDOT (Bridge and Ifju, 2018) is related to post-event or damage inspections. For bridges that have experienced impacts or other structural damage, UAS-based inspection can reduce the need to deploy UBITs onto potentially unstable structures. This capability allows preliminary condition assessments to be performed remotely, mitigating safety risks associated with accessing damaged bridges before their structural integrity is fully understood.

CHALLENGES

Multiple challenges have been identified in previous reports on UAS-based inspection, as summarized below.

Challenges in Navigation

Challenges in navigation may reduce flight stability, degrade positioning accuracy, and increase the risk of collisions or crashes, particularly in confined and complex bridge environments. Commonly reported challenges include:

- **Magnetic interference:** Large steel structural components may distort local magnetic fields and interfere with onboard magnetometers, potentially causing heading-estimation errors and unstable flight.
- **GNSS-denied environments:** Inspections conducted beneath bridge decks or near dense structural elements often experience degraded GNSS signals, reducing navigation accuracy and making stable hovering more difficult.
- **Wind and turbulent airflow:** Wind conditions around bridges can be highly variable because of interactions with structural geometry, affecting flight stability and increasing control difficulty.
- **Confined spaces and complex geometries:** Inspections beneath bridge decks, between girders, or within truss systems limit maneuvering space and increase collision risk, making stable navigation more challenging.
- **Hovering above water:** Reflective and low-feature water surfaces may degrade the performance of vision-based localization systems, making stable hovering more difficult.
- **Nesting birds and wildlife disturbance:** Birds may exhibit aggressive behavior toward UAS operating near nests, increasing safety risks and potentially interrupting inspection operations.

Several of these challenges, particularly magnetic interference, GNSS-denied environments, and wind-induced turbulence, are closely related to the navigation and flight capabilities of the UAS platform itself. Therefore, these challenges highlight the importance of selecting mature and well-established UAS platforms with robust localization capabilities, reliable sensor-fusion algorithms, and strong flight stability. In addition, careful mission planning, conservative flight strategies, and consideration of environmental conditions are critical to mitigating navigation-related risks and improving operational safety.

Challenges in Data Collection

Several challenges related to data collection have been reported in previous studies, potentially affecting inspection quality, defect detectability, and 3D reconstruction performance. Common challenges include:

- **Limited visibility of interior surfaces:** Structural components such as the interior faces of girders, areas within truss systems, or bearings may be partially occluded, making it difficult to achieve complete inspection coverage.
- **Insufficient image resolution:** Small defects, such as thin cracks or early-stage fatigue damage, may not be detectable if image resolution is inadequate because of inappropriate standoff distance, camera configuration, or motion blur.
- **Difficulty with 3D reconstruction:** Low-texture, reflective, or repetitive structural surfaces, particularly steel members, can hinder feature matching in 3D reconstruction, potentially resulting in incomplete models, holes, or geometric misalignment.
- **Challenging illumination conditions:** High contrast between bright sky backgrounds and dark structural areas beneath bridge decks may interfere with camera exposure control or autofocus performance, reducing image quality and defect visibility.
- **Shadow effects in thermal imaging:** Shadows cast by bridge components or surrounding environments may alter surface temperature distributions and reduce thermal contrast, potentially affecting the accuracy of thermal-anomaly detection and interpretation.

These challenges emphasize the importance of appropriate sensor selection, imaging configuration, lighting systems, and mission planning to ensure reliable data collection and sufficient inspection quality.

Overall, the challenges indicate that although camera-equipped UAS demonstrate strong potential for bridge inspection, further efforts are needed to improve navigation reliability, data quality, and robustness in complex bridge environments. Addressing these limitations is important for enabling broader, more reliable use of camera-equipped UAS in practical bridge inspection workflows.

CHAPTER 6: ADVANCED RESEARCH IN AUTOMATING THE UAS-BASED INSPECTION PIPELINE

Beyond the widely adopted manual-control approaches used in UAS-based bridge inspection, numerous studies have advanced efforts to automate the UAS-based inspection pipeline in several areas, including data collection and report generation.

AUTOMATED DATA COLLECTION

Recent years have seen increasing research efforts focused on enabling autonomous UAS inspection in GNSS-denied environments to improve inspection efficiency and repeatability and reduce pilot workload.

One key challenge for autonomous inspection is mission planning, which involves determining image-acquisition viewpoints or flight trajectories that achieve desired inspection quality while maintaining operational efficiency and safety. Most existing mission planning approaches are model-based and use prior geometric information about the target structure. For construction monitoring applications, Ibrahim et al. (2022b) proposed a computer vision-driven, optimization-based framework for automated reality-capture mission planning. For bridge inspection applications, Zhao et al. (2024) proposed an optimization-based mission planning framework that maximizes inspection efficiency while satisfying inspection quality constraints, whereas Wang et al. (2024) presented a rule-based mission planning approach that uses BrIM with integrated element information. In contrast, some studies have explored model-free online mission planning methods (Hepp et al., 2018; Chen et al., 2024), and commercial systems such as Skydio have developed autonomous UAS platforms capable of online viewpoint selection and 3D reconstruction without requiring prior models (Skydio, n.d.). These approaches dynamically determine viewpoints based on real-time observations, eliminating the need for preexisting geometric models as input. However, compared with model-based methods, they often provide less optimized inspection quality, less complete coverage, and lower operational safety because of the absence of prior structural knowledge and inspection objectives.

Another major challenge for autonomous flight in GNSS-denied environments is localization, that is, estimating the position and orientation of the UAS without reliable GNSS signals. To address this problem, odometry or simultaneous localization and mapping (SLAM) methods are commonly applied, using onboard sensor data from consumer-grade digital cameras, stereo cameras, depth cameras, inertial sensors, or LiDAR to estimate motion and reconstruct the environment. For example, Jung et al. (2020) demonstrated a LiDAR-based SLAM framework for bridge inspection beneath a bridge. Figure 18 illustrates the applied UAS platform, while Figure 19 compares trajectories estimated using GNSS (red) and LiDAR-based SLAM (blue). The significant deviation of the GNSS trajectories highlights the unreliability of positioning beneath bridges and demonstrates the importance of SLAM for autonomous navigation in such environments. Although LiDAR provides robust localization performance, its relatively high cost may limit widespread deployment. A lower-cost alternative is stereo visual odometry or stereo SLAM, which estimates motion using stereo camera observations (Benjumea et al., 2021). Figure 20 demonstrates the UAS platform equipped with stereo cameras for localization.

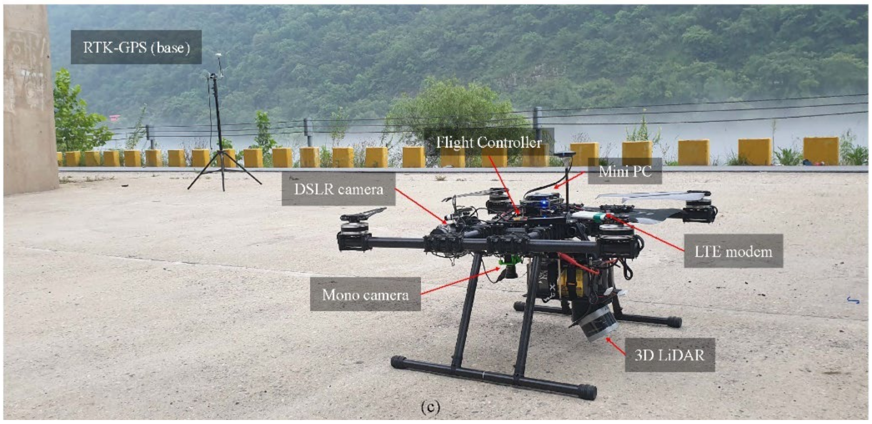


Figure 18. Photo. UAS platform equipped with a LiDAR-based SLAM system.

Source: Jung et al. (2020)

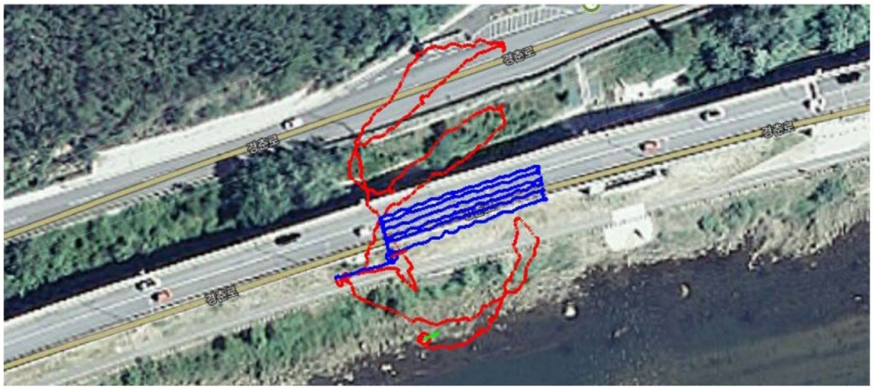


Figure 19. Graph. Comparison of trajectories estimated using GNSS (red) and LiDAR-based SLAM (blue).

Source: Jung et al. (2020)

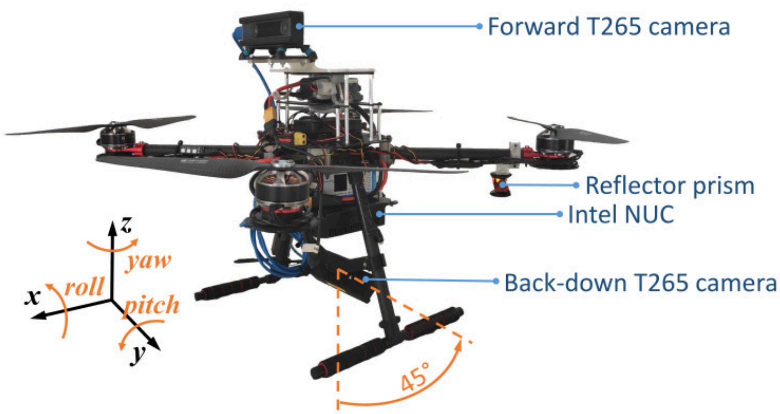


Figure 20. Photo. UAS platform equipped with stereo cameras.

Source: Benjumea et al. (2021)

Despite their promise for autonomous navigation, odometry and SLAM methods are subject to cumulative drift errors, which may degrade localization accuracy during long-duration missions. To mitigate this issue, some studies have introduced external references, such as fiducial markers (Wang et al., 2023) or ultrawideband (UWB) beacons (Bai et al., 2025) attached to bridge components, to provide global positioning constraints and reduce accumulated drift. However, these methods require deployment of fiducial markers or beacons in advance, increasing setup effort and reducing practicality for large-scale or rapid bridge inspection applications.

Overall, autonomous UAS inspection in GNSS-denied bridge environments remains an active research area with significant potential to improve inspection efficiency, repeatability, and scalability while reducing pilot workload. Existing studies have demonstrated promising progress in mission planning and localization, gradually enabling more reliable autonomous operations beneath bridges. However, challenges related to localization drift, navigation safety, inspection quality assurance, and dependence on prior structural information or external references still limit practical deployment in large-scale bridge inspection applications. Future developments are expected to focus on integrating robust localization, quality-aware mission planning, adaptive navigation, and real-time environmental perception into unified autonomous inspection systems, ultimately helping to bridge the gap between research demonstrations and practical field implementation.

AUTOMATED REPORT GENERATION

Previous state and federal reports have provided very limited discussion of automating the report-generation process, focusing primarily on early applications of computer vision or deep learning-based defect detection to assist post-inspection analysis. However, higher levels of automation in inspection-data analysis and report generation have been actively explored in academia.

For example, Lin et al. (2021) proposed an end-to-end pipeline for automating the UAS-based bridge inspection workflow, including data acquisition, 3D reconstruction, inspection and analysis, and report generation, as presented in Figure 21. In this study, aerial images are used to reconstruct a 3D point cloud model, on which inspectors perform damage detection and annotation within a virtual inspection environment. The labeled defects are then projected onto the reconstructed model with encoded 3D locations, which enables further defect size measurements and annotations, as presented in Figure 22. Based on these inspection and analysis data associated with the 3D model, an inspection report can be automatically generated, with an example presented in Figure 23.

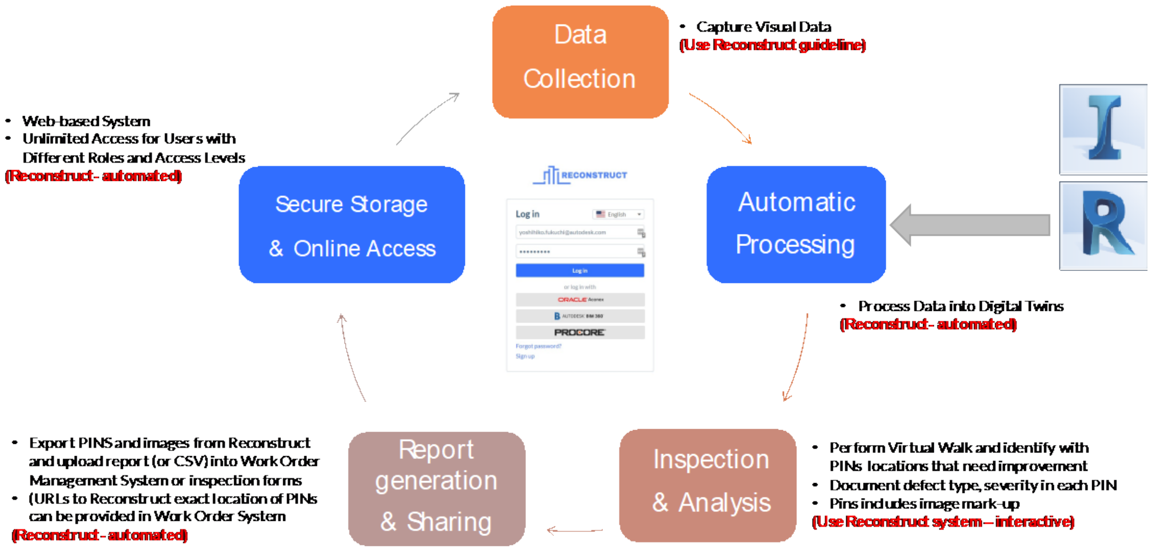


Figure 21. Diagram. End-to-end pipeline for automated UAS-based bridge inspection.

Source: Lin et al. (2021)

Figure 22. Illustration. Demonstration of defect measurement in a virtual inspection environment.

Source: Lin et al. (2021)

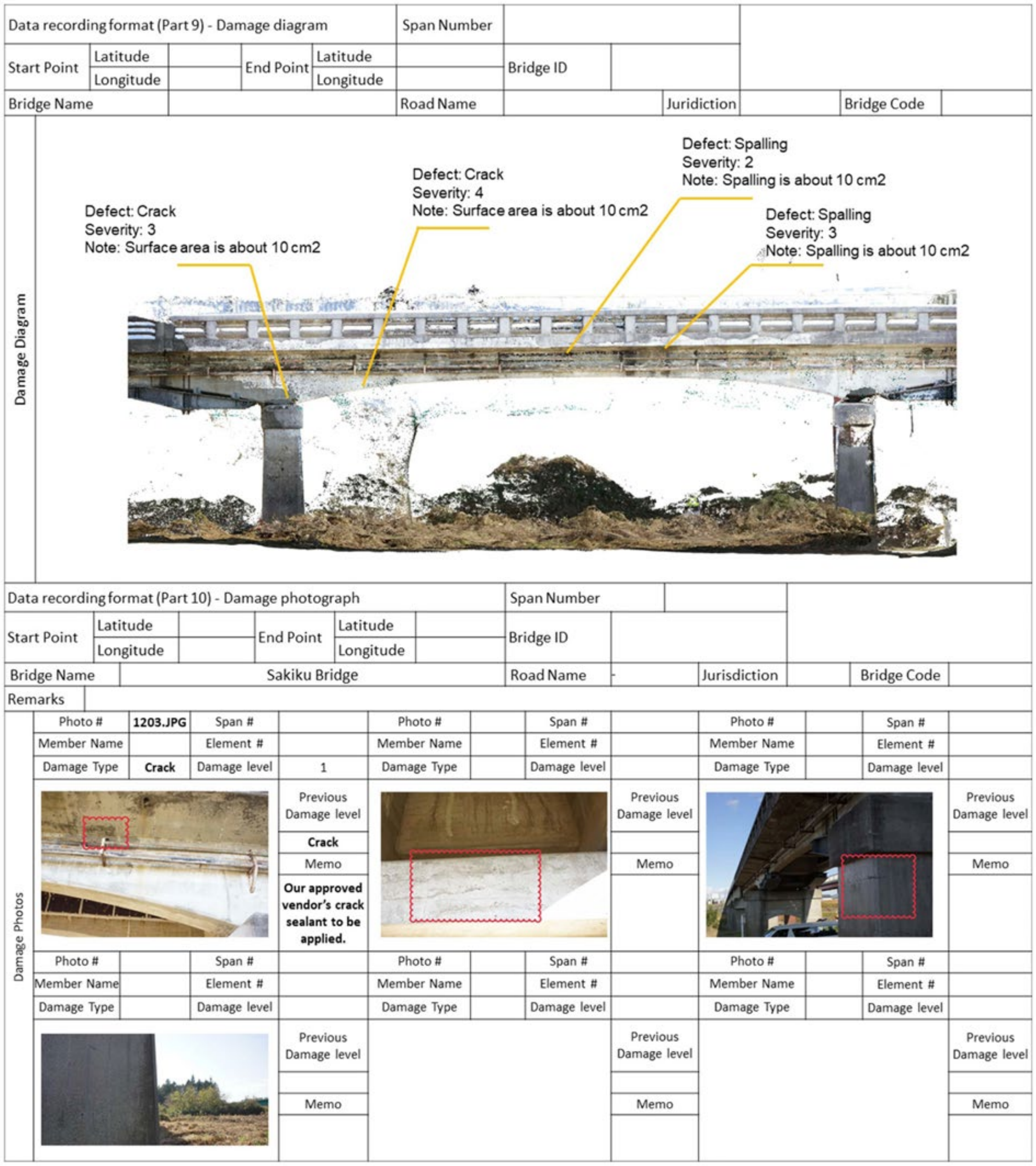


Figure 23. Screenshot. Example of an automatically generated inspection report.

Source: Lin et al. (2021)

The time and cost savings of the platform proposed by Lin et al. (2021) are presented in Figure 24. Traditional bridge inspection relies heavily on on-site activities for defect identification, measurement, and documentation. In contrast, reality-mapping-based inspection enables defect detection, measurement, and recording to be performed within a virtual environment. This shift reduces field workload, improves inspection efficiency, and enhances the consistency of digital records. Furthermore, the integration of AI-assisted defect detection and measurement has the potential to further reduce inspection time and costs while improving the scalability and efficiency of digital bridge inspection workflows.

Figure 24. Diagram. Time and cost comparisons of manual inspection, reality-mapping-based inspection, and near-future AI-assisted inspection.

Source: Lin et al. (2021)

Sacks et al. (2018) proposed a similar automated pipeline but with a stronger emphasis on generating BrIM with encoded defect and component information, which can subsequently support automated inspection documentation and report generation. In this framework, component detection and classification algorithms are applied to transform point cloud data into industry foundation classes (IFC) models, enabling extraction of structural component types together with their geometric and spatial information. Defects are then detected and projected onto the reconstructed 3D BrIM, allowing each defect to be associated with specific structural components and precise spatial locations. As a result, a BrIM with embedded defect information can be generated. Bartczak et al. (2025) proposed an inspection pipeline following a similar concept but placed greater emphasis on automated damage detection to support the automated inspection workflow. In this framework, deep learning-based defect detection algorithms are applied to identify potential defects in inspection images, and the resulting bounding boxes are used to crop and highlight defect areas. By automatically localizing and emphasizing potential defects, the system assists inspectors in prioritizing areas of interest and reducing the effort required for manual image review.

With recent advances in vision-language models (VLMs), studies have begun exploring the direct generation of natural language descriptions for inspection reports from inspection images, rather than limiting outputs to predefined defect classes as in conventional deep learning methods. Such approaches have the potential to provide more flexible and descriptive interpretations of bridge conditions and reduce dependence on large amounts of manually labeled training data required by conventional supervised deep learning methods.

Figure 25 presents an example from Wang and El-Gohary (2026), showing inspection images together with the automatically generated captions. Figure 25-a illustrates examples in which the generated descriptions closely match the reference annotations, whereas Figure 25-b presents partially correct predictions. These results demonstrate the potential of VLM-based approaches to assist automated inspection reporting while also highlighting the remaining challenges in achieving reliable and accurate free-form interpretation of complex structural defects.

Figure 25. Illustration. Examples of inspection image captioning using vision-language models.

Source: Wang and El-Gohary (2026)

360-DEGREE CAMERAS FOR BRIDGE INSPECTION

360-degree cameras are imaging devices that use one or more wide-angle lenses to capture a full spherical view of the surrounding environment. These cameras are a cost-effective sensing tool with the advantage of capturing the entire surrounding environment in a single acquisition. This characteristic is particularly beneficial for bridges with complex geometries, where conventional cameras would require multiple camera orientations from the same position to achieve complete coverage. Although researchers have explored the application of 360-degree cameras to highway construction inspection (NASEM, 2022), the reviewed state or federal case study reports have not extensively explored the application of 360-degree cameras in bridge inspection. However, multiple research studies have explored the application of 360-degree imaging for bridge and infrastructure inspection.

In the case study by Humpe (2020), a UAS equipped with a 360-degree camera was deployed to inspect the underside of a bridge, as presented in Figure 26. The collected 360-degree images were used for defect identification, and the inspection performance was compared with that of a conventional HD camera. The results demonstrated the feasibility of applying 360-degree cameras to bridge inspection, particularly for efficiently capturing comprehensive visual information in complex environments.

Another study by Sen et al. (2025) also applied 360-degree imaging to bridge inspection. However, the study reported that some thin cracks were not detectable in the 360-degree images due to the lower effective resolution resulting from the large field of view (FOV). This limitation highlights the trade-off between comprehensive coverage and defect detectability, suggesting that 360-degree cameras may be more suitable for rapid condition assessment or inspection of larger defects rather than detailed crack detection.

Figure 26. Photo. UAS equipped with a 360-degree camera.

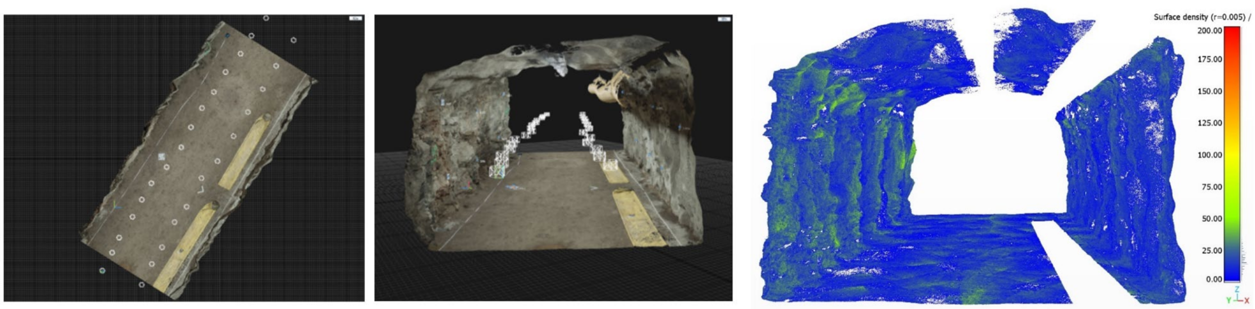
Source: Humpe (2020)

In addition to visual inspection, attempts have also been made to perform 3D reconstruction using 360-degree images. Figure 27 presents an example of reconstructing urban scenes containing a highway bridge, demonstrating the feasibility of 360-degree image-based 3D reconstruction. The ability of 360-degree cameras to capture the entire surrounding environment in a single acquisition provides advantages in improving coverage efficiency and reducing the number of viewpoints required for reconstruction.

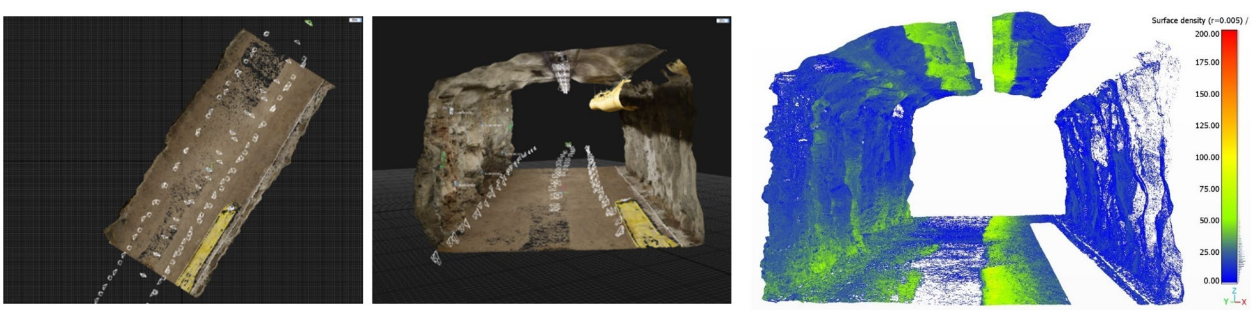
Figure 27. Point cloud visualization. Demonstration of urban scene reconstruction using 360-degree images.

Source: Cera and Campi (2022)

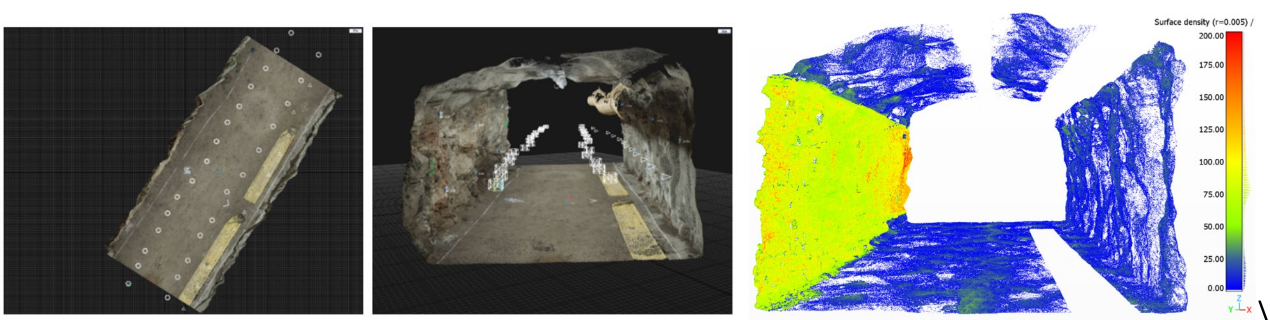
Figure 28 illustrates another example of applying 360-degree imagery for tunnel reconstruction (Janiszewski et al., 2022). The study concluded that 360-degree image-based reconstruction offers higher efficiency than conventional camera-based reconstruction, although the resulting reconstruction quality was slightly lower. To balance efficiency and reconstruction accuracy, the study suggested combining 360-degree images for comprehensive coverage with conventional images targeting critical regions, enabling more efficient yet higher-quality reconstruction of structures with complex geometries.



(a) 360-degree camera



(b) Digital single-lens reflex (DSLR) camera



(c) 360-degree camera and DSLR camera

Figure 28. Point cloud visualization. Tunnel reconstruction results using 360-degree images.

Source: Janiszewski et al. (2022)

Overall, while UAS technologies remain highly valuable for bridges with excessive heights, difficult access conditions, or components that cannot be safely reached from the ground, 360-degree cameras offer a compelling and practical alternative for many bridge inspection scenarios. When bridge elements are reasonably accessible, 360-degree cameras offer a promising and economical solution for rapid inspection, broad scene coverage, and potentially 3D reconstruction with substantially lower deployment complexity. Because they follow a similar workflow of data acquisition and reality-mapping, 360-degree cameras have comparable applicability to UAS for routine inspections and can also serve as a supporting tool for other types of inspections. Despite these advantages, the reviewed state and federal case study reports have not yet substantially explored the role of 360-degree imaging as a complementary digital inspection technology. Future pilot studies should therefore evaluate the use of 360-degree cameras for suitable bridge types and inspection tasks, and future digital inspection programs should consider incorporating 360-degree imaging alongside UAS and other sensing technologies.

CHAPTER 7: PRELIMINARY BENEFIT–COST ANALYSIS

In this section, findings and data from the reviewed literature are used to compare the data collection efficiency, cost, and quality across different types of equipment, including UBITs, manually controlled camera-equipped UAS, automatically controlled camera-equipped UAS, UAS with LiDAR, terrestrial laser scanning, and 360-degree cameras. This section provides a preliminary analysis based on the reviewed literature, and a more comprehensive analysis should be the subject of future studies. Such future analyses should account for the latest regulatory changes, up-to-date cost assumptions, evolving drone technologies, and more state- and agency-specific operational conditions.

The estimated equipment costs for different bridge inspection methods are summarized in Table 4. Costs are calculated based on assumed service life, maintenance requirements, and annual inspection frequency.

Table 4. Equipment Cost Estimation

Method	Initial Cost	Maintenance Assumption	Service Life	Usage	Estimated Equipment Cost
UBIT + maintenance of traffic	Included*	Included*	Included*	Included*	$2,000–$3,500/day
UAS (Consumer–grade digital camera)	$10,000–$25,000	$3,000–$5,000/year	3–5 years	120–180 days /year	$30–$110/day
UAS (LiDAR)	$50,000 –$100,000	$5,000–$10,000/year	3–5 years	120–180 days /year	$80–$360/day
Terrestrial laser scanning	$70,000–$150,000	$5,000–$10,000/year	5–8 years	150–250 days /year	$50–$270/day
360–degree camera	$500–$1,000	Minimal	2–4 years	150–250 days /year	$1–$3/day

* Rental rates, including required traffic control, and operators.

To compare the efficiency of different inspection approaches, this analysis assumes a representative beam bridge with the following characteristics:

- Bridge width: 12 m
- Span length: 20 m
- Number of spans: 6
- Number of girders: 12
- Girder depth: 0.5 m
- Vertical clearance: 10 m
- Substructure: 5 piers with a total of 25 columns and 2 abutments

The estimated inspection time for different methods is detailed in Appendix A, and the estimated inspection time, cost, and inspection-quality comparisons are summarized in Table 5.

Table 5. Comparison of Inspection Time, Cost, and Inspection Quality Among Bridge Inspection Methods

Method	Inspection Time	Inspection Cost	Inspection Quality
UBIT + maintenance of traffic	8 h	\$2,000–\$3,500 equipment + \$50/person·h × 4 personnel × 8 h = \$3,600–\$5,100	Conventional close-range visual inspection
UAS (Consumer-grade digital camera) - manual flight	12 h. Although a single camera-equipped UAS may require longer inspection time than UBIT, only 2 crew members are required. Simultaneous operation of 2 UAS could further reduce inspection time by ~25%.	\$30–\$110/day × 2 days + \$50/person·h × 2 personnel × 12 h = \$1,200–\$1,400	Assuming standoff distance = 2 m and camera resolution = 8000 × 6000 pixels, estimated surface sampling distance (SSD) ≈ 0.01 in, below the insignificant crack threshold (0.012 in.)
UAS (Consumer-grade digital camera) - autonomous flight	6 h. Reduces required personnel by 2 crew members and inspection duration by ~25%.	\$30–\$110/day × 1 day + \$50/person·h × 2 personnel × 6 h = \$600–\$700	Assuming standoff distance = 2 m and camera resolution = 8000 × 6000 pixels, estimated SSD ≈ 0.01 in, below the insignificant crack threshold (0.012 in.)

Method	Inspection Time	Inspection Cost	Inspection Quality
UAS (LiDAR)	6 h. Reduces required personnel by 2 crew members and inspection duration by ~25%.	\$80–\$360/day × 1 day + \$50/person·h × 2 personnel × 6 h = \$700–\$1,000	Assuming 0.24 M points/s, coverage = 0.5 m × 0.5 m per second, and 50% useful points, estimated density ≈ 0.48 M points/m² (~700 points/in²). Estimated sampling distance ≈ 0.05 in, above the 0.012 in threshold.
Terrestrial Laser Scanning	12 h. Parallel operation of 2 TLS units may reduce inspection duration by ~25%.	\$50–\$270/day × 2 days + \$50/person·h × 2 personnel × 12 h = \$1,300–\$1,500	Assuming 2 M points/s, 3 min/station, and 25% useful points, each station collects ~90 M useful points. For 25 m² coverage/station, density ≈ 3.6 M points/m². Estimated sampling distance ≈ 0.02 in, above the 0.012 in threshold.
360-degree camera	3 h. Reduces required personnel by 2 crew members and inspection duration by ~60%.	\$1–3/day × 0.5 day + \$50/person·h × 2 personnel × 3 h = \$300	Assuming 7680 × 3840 resolution (~0.000818 rad/pixel), estimated surface sampling distance ≈ 8 mm (0.31 in) above the 0.012 in threshold.

Based on this preliminary analysis, manually controlled camera-equipped UAS can reduce inspection costs by approximately 65% compared with UBIT-based inspection for routine inspection of the assumed bridge while achieving image quality sufficient to satisfy the defect detectability requirements suggested by AASHTO (2019). Autonomous UAS inspection can further improve efficiency and reduce labor requirements, resulting in even higher cost reductions. These findings highlight the significant potential of autonomous navigation to increase the economic benefits of UAS-based inspection.

When equipped with LiDAR sensors, UAS can directly generate point cloud data during inspection, eliminating the need for subsequent computer vision image-based and video-based 3D reconstruction. However, the increased equipment cost results in slightly higher overall inspection costs compared with camera-equipped UAS. Although point cloud density strongly depends on flight speed, sensor configuration, and scanning parameters, with a similar inspection time as camera-equipped UAS, the estimated sampling density of UAS-mounted LiDAR in this analysis, assuming an inspection time similar to that of camera-equipped UAS, does not satisfy the crack detectability threshold suggested by AASHTO (2019). Terrestrial laser scanning requires longer acquisition time and therefore incurs higher labor costs than UAS-based approaches, although it can achieve higher point density and geometric accuracy than UAS-mounted LiDAR. Nevertheless, data quality depends heavily on the height of the bridge. Under the assumed configurations, the estimated resolution remains insufficient to satisfy the target crack-detection threshold. This analysis shows that while LiDAR-based methods are advantageous for geometric measurement and 3D documentation, they may be less suitable for identifying small surface defects without additional close-range inspection.

The 360-degree camera approach demonstrates the lowest estimated cost and shortest inspection duration among the evaluated methods, suggesting strong potential for rapid condition assessment and efficient documentation. Compared with UAS-mounted or conventional handheld cameras, the large FOV of 360-degree cameras significantly improves inspection efficiency and reduces deployment costs while maintaining the capability to detect many larger defects, such as concrete spalling and steel rust, and to support 3D reality-mapping. However, the larger FOV can lead to a relatively higher surface sampling distance. Therefore, achievable image resolution is highly dependent on standoff distance, which may limit crack detectability for large or tall bridge structures. In addition, the applicability of 360-degree cameras is limited for bridges over water or other inaccessible environments because data collection depends on inspector access. Future studies should provide a more detailed analysis of this cost-effective technology’s potential to complement UAS inspections.

Overall, these comparisons indicate that no single method is universally optimal for all bridge inspection scenarios. Instead, appropriate selection should consider bridge geometry, accessibility, inspection objectives, required defect detectability, and budget constraints to achieve an effective balance among cost, efficiency, and inspection quality.

CHAPTER 8: INVENTORY-LEVEL PRIORITIZATION OF BRIDGES FOR UAS-BASED INSPECTION

The objective of this chapter is to develop an inventory-level screening approach for identifying bridges where UAS-based inspection is likely to provide the greatest practical value. Rather than treating UAS as equally beneficial for all bridges, the analysis recognizes that the economic and inspection quality benefits of camera-equipped UAS deployment depend on bridge accessibility, traffic control requirements, inspection complexity, and bridge site conditions. Bridges that are difficult to access, costly to inspect using conventional methods, or associated with significant traffic disruption may offer greater opportunities for camera-equipped UAS to improve inspection efficiency and enhance the documentation of conditions. This chapter therefore evaluates key inventory attributes that can be used to prioritize bridges for UAS-based inspection and support more targeted implementation of digital inspection programs.

CONSIDERATIONS FOR INVENTORY-LEVEL PRIORITIZATION

To identify bridges that may benefit most from UAS-based inspection, several factors should be considered because they influence inspection accessibility, traffic impacts, operational efficiency, and potential cost savings. These factors do not determine UAS applicability by themselves, but they provide a practical basis for screening bridge inventories and identifying high-value candidates for further evaluation. The key considerations are summarized below.

Traffic Impact Considerations

- Average daily traffic (ADT)
- Detour length
- Highway type carried by the bridge

These factors affect the difficulty of implementing traffic control measures and the economic impacts associated with lane closures or traffic disruption during inspection. Bridges with higher ADT, higher-level road classifications, or longer detour distances generally impose greater societal and economic costs when conventional inspection methods are used. For such bridges, UAS-based inspection may provide greater value by reducing the need for extensive traffic control, shortening field deployment time, and limiting disruption to the traveling public.

Accessibility Considerations

- Service beneath the bridge
- Vertical clearance

The type of service beneath the bridge (e.g., roadway, railway, or waterway) and bridge clearance directly influence inspection accessibility. Bridges crossing waterways or other difficult-to-access areas are often more challenging to inspect using conventional methods. Similarly, bridges with large vertical clearances may require specialized access equipment or may limit the ability of inspectors to observe components safely and efficiently from the ground. These conditions can increase the potential benefit of camera-equipped UAS deployment.

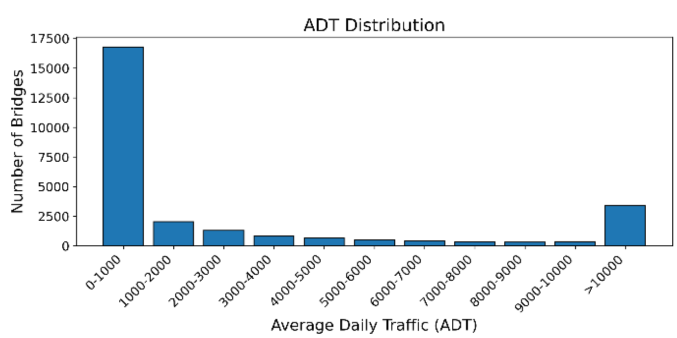
Bridge Size and Inspection Scope Considerations

- Bridge length
- Bridge width

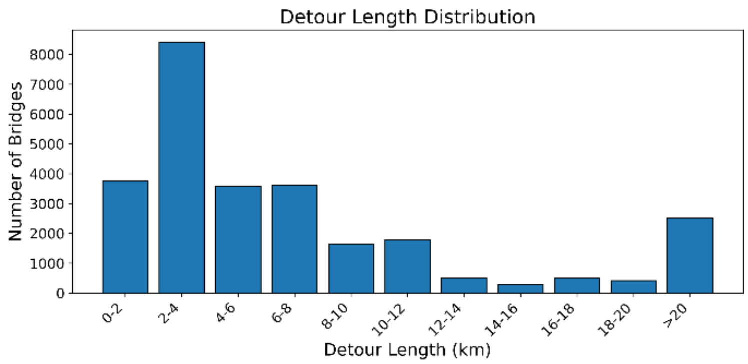
Bridge dimensions also affect the applicability of camera-equipped UAS inspection. Larger bridges generally require more inspection effort, longer field time, and more extensive documentation. In these cases, UAS may provide benefits by improving access to large components, supporting more comprehensive visual documentation, and enabling efficient imagery collection for digital records or 3D reconstruction. However, bridge size should be considered together with accessibility and inspection requirements, because large bridges with easy ground access may not always benefit equally from camera-equipped UAS deployment.

Figure 29 demonstrates the distribution of these factors within the IDOT bridge inventory. Most bridges carry county highways and have relatively low ADT values and detour lengths (Figure 29-a to Figure 29-c), although a subset of bridges carry higher traffic volumes and are associated with longer detour distances. These bridges may represent higher-priority candidates for UAS-based inspection because conventional inspection activities could result in greater traffic control impacts and user costs.

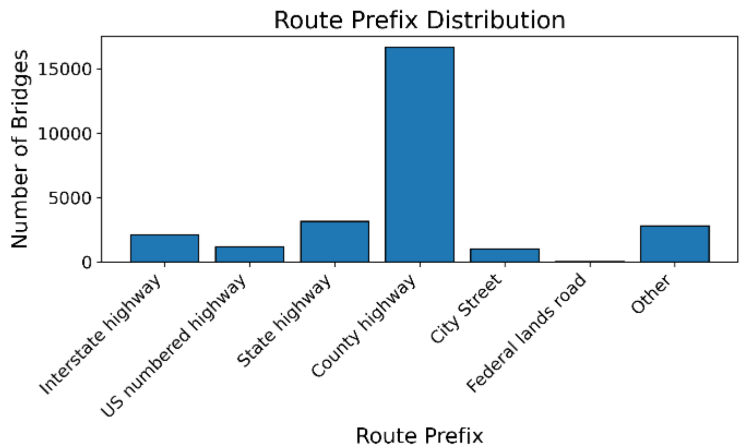
As presented in Figure 29-d, many bridges cross waterways, for which UAS-based inspection could provide significant accessibility benefits compared with conventional approaches. Clearance information in the inventory is only available for bridges over traffic, and the distribution is presented in Figure 29-e. The results indicate that approximately two-thirds of bridges over traffic have clearances between 4 and 6 m, while around one-third have clearances greater than 12 m. Bridges with larger clearances may be more difficult to inspect from the ground and may therefore represent stronger candidates for UAS-based visual inspection. Bridge width and length exhibit wider distributions as presented in Figure 29-f and Figure 29-g. The presence of many bridges with larger dimensions suggests that UAS-based inspection may provide additional potential benefits for cases requiring extensive visual coverage and documentation.



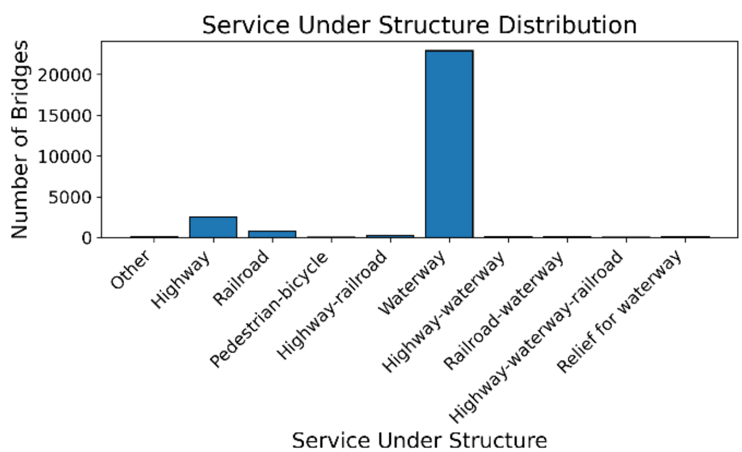
(a) ADT



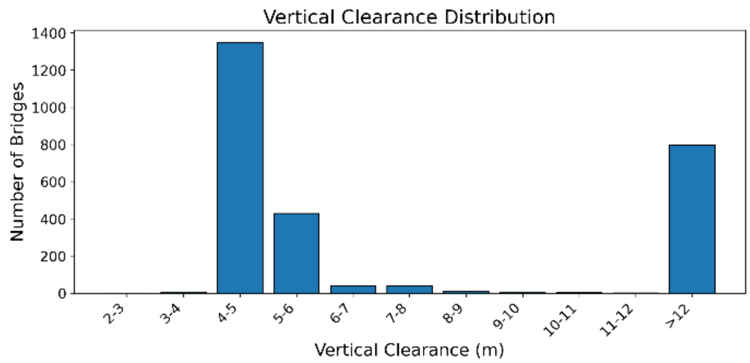
(b) Detour length



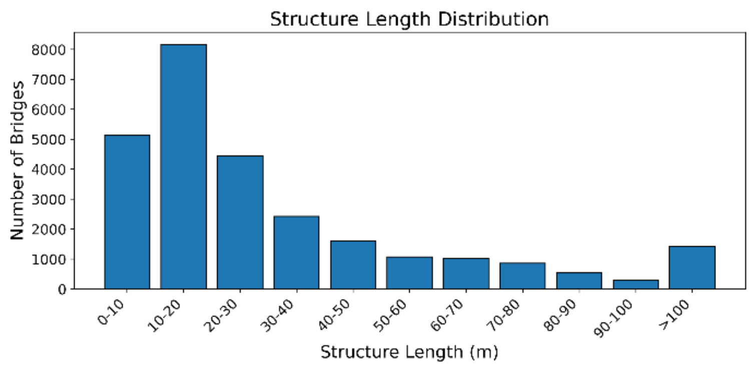
(c) Route prefix



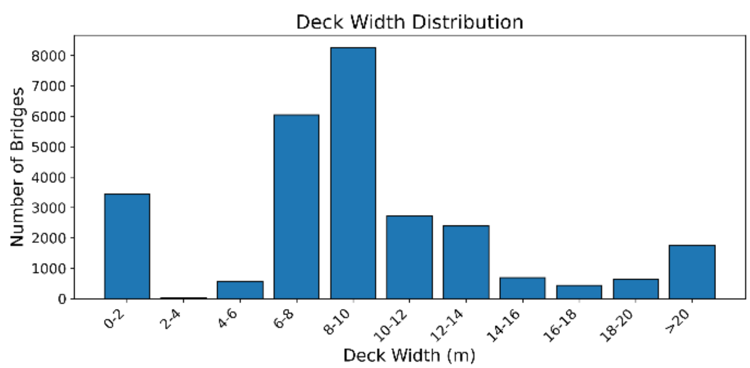
(d) Service under structure



(e) Vertical clearance



(f) Structure length



(g) Deck width

Figure 29. Graph. Distribution of key bridge parameters relevant to UAS-based inspection applicability within the IDOT bridge inventory.

Source: Authors

RATING FOR UAS DEPLOYMENT PRIORITY

Based on the considerations discussed above, an inventory-level rating approach was developed to quantify the applicability and potential benefits of UAS-based inspection, as summarized in Table 6. The proposed approach assigns scores to individual bridge characteristics according to their expected influence on the benefits of camera-equipped UAS deployment. Higher scores correspond to bridge conditions where UAS-based inspection is expected to provide greater advantages over conventional inspection approaches, particularly in terms of accessibility, reduced traffic disruption, field efficiency, and improved visual documentation.

Table 6. Rating Framework for Applicability of UAS-Based Inspection

Item	3 points	2 points	1 point	0 points
Average daily traffic (ADT)	≥ 10,000	≥ 5,000	≥ 1,000	< 1,000
Detour length	≥ 15 km	≥ 10 km	≥ 5 km	< 5 km
Highway type carried by the bridge	Interstate highway	US-numbered highway/ State highway	County highway/ City street	Other
Service beneath the bridge	Waterway / mixed service including waterway	Railroad / Highway-railroad	Highway	Pedestrian-bicycle/other
Vertical clearance	≥ 14 m	≥ 10 m	≥ 7 m	< 7 m
Bridge length	≥ 30 m	≥ 20 m	≥ 10 m	< 10 m
Bridge width	≥ 15 m	≥ 10 m	≥ 5 m	< 5 m

For each bridge, the total UAS inspection priority score is calculated as the sum of all factor scores, with a maximum possible score of 21 points. Bridges with higher scores are expected to benefit more from UAS-based inspections due to increased challenges associated with accessibility, traffic impacts, or inspection scope. The resulting score distribution across the bridge inventory is presented in Figure 30.

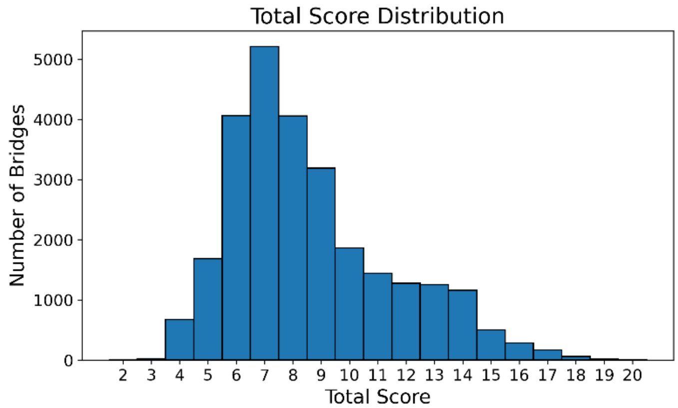


Figure 30. Graph. Distribution of applicability scores for UAS-based bridge inspection.

Source: Authors

The score distribution indicates that many bridges receive relatively low priority scores because of their small size, low traffic volume, or more favorable accessibility conditions. However, a substantial subset of bridges receives high scores, suggesting strong potential value from UAS-based inspection. Consequently, the proposed rating framework provides a practical inventory-level approach for prioritizing bridges where camera-equipped UAS deployment is most likely to yield the greatest improvements in safety, accessibility, efficiency, and cost-effectiveness. The resulting rating is intended to support prioritization rather than serve as a definitive decision rule. In practice, final decisions regarding UAS deployment should also consider site-specific constraints, inspection objectives, weather conditions, regulatory requirements, airspace restrictions, available personnel, and the need for hands-on access. Therefore, the rating framework should be viewed as a screening tool that helps identify bridges or groups of bridges where UAS-based inspection may offer the greatest economic and inspection-quality impact.

CHAPTER 9: UAS INSPECTION DEMONSTRATION

This chapter outlines three camera-equipped UAS inspections conducted in Illinois, as summarized in Table 7. The selected bridges represent different structure types, condition ratings, operational environments, and structural scales, enabling comparison of camera-equipped UAS performance across a range of inspection scenarios.

This chapter presents the structural characteristics of the selected bridges, the data collection procedures, and the lessons learned from each inspection. The objective of this chapter is to evaluate the feasibility, advantages, and limitations of UAS-assisted bridge inspection and provide practical insights that can support future implementation of UAS technologies in IDOT bridge inspection programs.

Table 7. Summary of Bridges for Demonstration

Bridge No.	0103277	0580128	0410067
Number of spans	3	1	4
Structure type	Reinforced concrete beam bridge	Prestressed concrete beam bridge	Steel continuous girder bridge
Year built	1969	1998	1972
Length	25.3 m (83 ft)	41.9 m (137 ft)	58.8 m (193 ft)
Condition rating (deck/ superstructure /substructure/ channel)	6/6/7/6	6/8/7/8	5/6/6/N
Priority score	8	13	14
Feature crossed	Embarras River	Stevens Creek	ILL-37
Feature carried	TR 269A (county road)	US 36	I-64 WB
Average daily traffic (ADT)	275	7,250	6,400

BRIDGE NO. 0103277

Structural Information

The first bridge selected for inspection demonstration is Bridge No. 0103277, located near Tolono, Illinois. It is a three-span reinforced concrete beam bridge with a total length of 25.3 m (83 ft). Constructed in 1969, the bridge carries TR 269A over the Embarras River and accommodates two lanes of traffic. Views of the bridge from above and below are presented in Figure 31. According to the bridge inventory records, the structure is in satisfactory to good condition. The bridge received a priority score of 8, indicating a moderate level of suitability for UAS-assisted inspection based on the proposed bridge selection framework.

(a) Upper-side view of the bridge

(b) Bottom-side view of the bridge

Figure 31. Photo. View of Bridge No. 0103277.

Source: Authors

Data Collection

The data collection was conducted by a three-person team consisting of an FAA Part 107-certified remote pilot, a visual observer, and a team leader. The data collection plan included the acquisition of both consumer-grade digital imagery and thermal imagery to support visual inspection, thermal condition assessment, and computer vision image-based and video-based 3D reconstruction. Flight missions were manually planned by the pilot, with sufficient image overlap to facilitate reliable 3D reconstruction. A commercial UAS was operated both above and beneath the bridge to capture data from multiple viewpoints and ensure comprehensive coverage of the deck, superstructure, and substructure. In total, 1,202 consumer-grade digital images were collected for visual inspection and 3D reconstruction. The data collection process took approximately two hours and was completed without any safety incidents or operational issues involving the UAS, surrounding personnel, or traffic.

Data Processing and Analysis

The collected aerial images were manually reviewed to identify visible defects. Overall, the bridge was found to be in good condition. However, spalling was observed on several columns, consistent with defects visible in inspection records. A side-by-side comparison of the UAS-collected image and a photograph from the inspection report is presented in Figure 32. The UAS was able to approach the target column closely and capture higher-resolution images, providing clearer visualization and documentation of the defect.

Figure 32. Photo. Comparison of a UAS-collected image (left) and a photograph from a previous inspection (right) showing column spalling on Bridge No. 0103277.

Source: Authors

Computer vision image-based 3D reconstruction was performed using Agisoft Metashape Pro (Agisoft, 2024) with the collected images. An overview of the reconstructed model is presented in Figure 33. The results demonstrate successful reconstruction of the bridge deck and substructure, with a high level of geometric completeness and visual detail. The superstructure was also successfully reconstructed, while the reconstruction quality was comparatively lower because of challenging image-acquisition geometries, limited illumination beneath the bridge deck, and the relatively low-texture surfaces of the concrete members.

(a) Upper view of the reconstructed model

(b) Bottom view of the reconstructed model

(c) Side view of the reconstructed model

Figure 33. Point cloud visualization. Visualization of the reconstructed model of Bridge No. 0103277.

Source: Authors

Conclusions and Challenges

The demonstration on Bridge No. 0103277 provided an opportunity to evaluate the process of UAS-based data collection for bridge inspection and computer vision image-based 3D reconstruction. The collected consumer-grade digital imagery provided close-range visual details that supported manual defect review and enabled the successful reconstruction of the bridge deck, substructure, and superstructure, resulting in a detailed digital representation of the bridge.

Several practical challenges were also observed during the case study. First, reduced reconstruction quality was observed in poorly illuminated and low-texture areas beneath the bridge, which limited the computer vision image-based reconstruction quality. The commercial UAS employed in this demonstration did not allow the use of add-on lighting due to hardware-specific payload capacity restrictions. Therefore, future inspections should consider payload capacity for add-on lighting when selecting UAS platforms. In addition, the confined space beneath the bridge introduced data collection challenges from both quality and safety perspectives. To avoid collisions with structural members, the pilot was required to operate the UAS at relatively low speeds and perform frequent manual adjustments, reducing data collection efficiency and increasing operational complexity.

BRIDGE NO. 0580128

Structural Information

The second inspection demonstration was carried out on Bridge No. 0580128, located near Decatur, Illinois. This structure is a one-span prestressed concrete beam bridge with a total length of 41.9 m (137 ft). Constructed in 1998, the bridge carries US 36 over Stevens Creek and accommodates four lanes of traffic. Views of the bridge from above and below are presented in Figure 34. According to bridge inventory records, the structure is in good to very good condition, except that the deck is in satisfactory condition. The bridge has a priority score of 13, ranking it among the bridges most suitable for UAS-assisted inspection.

(a) Upper view of the bridge

(b) Bottom view of the bridge

Figure 34. Photo. Views of Bridge No. 0580128.

Source: Authors

Data Collection

Data collection was conducted by a two-person team consisting of an FAA Part 107-certified remote pilot and a visual observer. The data collection plan included acquiring close-up imagery. Flight missions were manually planned by the pilot, with sufficient image overlap to facilitate reliable reconstruction. Due to the relatively large space of around 1 m between girders, the pilot was able to fly the UAS between girders to acquire close-range images on the superstructure.

In total, 2,985 consumer-grade digital images were collected for visual inspection and 3D reconstruction, and the data collection process took approximately 3.5 hours. The data collection process was completed with no safety incidents or operational issues involving surrounding personnel or traffic; however, a propeller struck a concrete beam while the UAS was maneuvering within a confined space. The impact did not result in significant damage, loss of control, or a crash.

Data Processing and Analysis

The collected images were first manually reviewed to identify visible defects. Although the bridge is generally in good condition, concrete spalling and exposed reinforcing steel were observed on the underside of the bridge deck, as presented in Figure 35. These defects were clearly captured by the UAS imagery. However, because of the bridge's relatively large span and the location of the defects beneath the deck, obtaining high-quality images using conventional ground-based photography would have been challenging. This example demonstrates the capability of UAS-assisted inspection to effectively document deterioration in areas that are difficult to access and visualize using traditional inspection methods.

Figure 35. Photo. Comparison of a UAS-collected image (left) and a photograph from a previous inspection (right) showing concrete spalling and exposed rebar on Bridge No. 0580128.

Source: Authors

Computer vision image-based 3D reconstruction was performed was performed using Agisoft Metashape Pro (Agisoft, 2024) with the collected consumer-grade digital images. An overview of the reconstructed model is presented in Figure 36.

Figure 36. Point cloud visualization. Visualization of the reconstructed model of Bridge No. 0580128.

Source: Authors

Conclusions and Challenges

The demonstration on Bridge No. 0580128 highlighted the enhanced accessibility provided by UAS-assisted inspection for bridges with relatively long spans. In such cases, obtaining close-range images of midspan areas using conventional inspection methods can be difficult and inefficient. The demonstration also validated the feasibility of operating a UAS between girders, enabling the collection of high-resolution images with greater detail than would typically be achievable using ground-based viewpoints.

Several practical challenges were also identified. Although many commercial UAS platforms are equipped with obstacle avoidance systems, the minimum obstacle-detection distance is often too large for operation within the confined spaces between girders. As a result, the obstacle avoidance function prevented the UAS from entering these areas and therefore had to be disabled during the inspection. Operating without obstacle avoidance increased the difficulty of flight control and led to a minor propeller strike against a girder. In addition, close-range inspection required manual capture of a large number of images, significantly increasing pilot workload. The development of UAS platforms with autonomous navigation and automated data collection capabilities could substantially reduce operator workload while improving the reliability and efficiency of bridge inspections.

BRIDGE NO. 0410067

Structural Information

The third inspection demonstration was carried out on Bridge No. 0410067, located near Mt. Vernon, Illinois. This structure is a steel beam bridge consisting of a two-span main unit and two approach spans, with a total length of 58.8 m (193 ft). Constructed in 1972, the bridge carries I-64 WB over IL-37 and accommodates two lanes of traffic. Views of the bridge from above and below are presented in Figure 37. According to the inventory, the bridge was in fair to satisfactory condition; an overheight vehicle had previously struck the steel girders, resulting in significant deformation. The bridge has a priority score of 14, ranking it among the bridges most suitable for UAS-assisted inspection.

(a) Upper-side view of the bridge

(b) Bottom view of the bridge

Figure 37. Photo. Views of Bridge No. 0410067.

Source: Authors

Data Collection

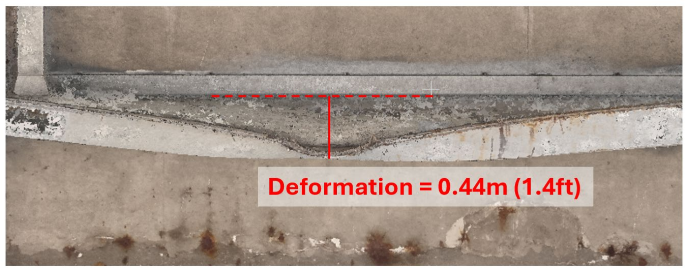
Data collection was conducted by a two-person team consisting of an FAA Part 107-certified remote pilot and a visual observer. The data collection plan included acquiring close-up imagery. Flight missions were manually planned by the pilot, with sufficient image overlap to facilitate reliable reconstruction.

In total, 1,463 consumer-grade digital images were collected for visual inspection and 3D reconstruction, and the data collection process took approximately two hours. Because the bridge is above another roadway, one lane beneath the bridge was closed for safe operation, while the traffic above the bridge was not affected. The data collection process was completed without any safety incidents or operational issues involving the UAS, surrounding personnel, or traffic.

Data Processing and Analysis

Computer vision image-based 3D reconstruction was performed using Agisoft Metashape Pro (Agisoft, 2024) with the collected images. An overview of the reconstructed model is presented in Figure 38-a. The reconstruction successfully captured the overall geometry of the bridge, including the deck, girders, diaphragms, and substructure components, providing a comprehensive digital representation of the structure. Based on this model, the girder deformation caused by the overheight vehicle impact can be visualized and measured, as presented in Figure 38-b. The digital record provides a detailed representation of the deformation geometry and enables quantitative measurements in multiple dimensions. In addition to lateral displacement, the model can be used to evaluate other deformation characteristics, such as the extent, shape, and spatial distribution of the damaged area, thereby supporting a more comprehensive assessment of structural damage.

(a) Bottom-side view of the deformed girders



(b) Bottom view of the deformed girders

Figure 38. Point cloud visualization. Visualization of deformed girders in the reconstructed model of Bridge No. 0410067.

Source: Authors

Conclusions and Challenges

The demonstration on Bridge No. 0410067 shows the feasibility of using UAS-based 3D reconstruction for structural deformation measurement and documentation. The collected imagery enabled the generation of a detailed 3D model that accurately captured the geometry of the bridge and the deformation of the steel girders. Compared with conventional photographs, the reconstructed model provided a more comprehensive digital record of the damaged girders and enabled quantitative measurements of deformation characteristics from multiple viewpoints. Such capabilities can support condition assessment, damage documentation, and future monitoring of structural changes.

In addition, although one lane beneath the bridge was closed for safety, the inspection team was able to remain at a safe distance from the adjacent active traffic lane rather than working from ladders or other elevated access equipment near traffic. This outcome demonstrates the potential of UAS-assisted inspection to improve inspector safety by reducing exposure to traffic hazards and minimizing the need for personnel to access difficult or hazardous locations.

Several practical challenges were identified during the demonstration. Because traffic remained active beneath the bridge, the pilot had to operate cautiously to ensure that the UAS remained clear of the open traffic lane, increasing operational complexity and pilot workload. In addition, the smooth and relatively featureless surfaces of the steel girders resulted in localized holes in the computer vision image-based 3D reconstruction model. These limitations highlight the need for more robust 3D reconstruction approaches to improve model completeness and reliability for low-texture components, such as steel girders.

SUMMARY

The data collection and processing durations, along with the major findings and challenges identified during the three bridge inspection demonstrations, are summarized in Table 8. Overall, the case studies demonstrate that camera-equipped UAS can improve inspection accessibility, defect documentation, inspector safety, and 3D reconstruction capabilities. At the same time, challenges related to navigation, active traffic, and reconstruction quality in low-texture or poorly illuminated environments remain and warrant further research and development.

Table 8. Summary of UAS Inspection Demonstrations and Key Findings

Bridge No.	0103277	0580128	0410067
Inspection time	2 hours	3.5 hours	2 hours
Number of images	1,202	2,985	1,463
Time estimation for 3D reconstruction	2.5 hours	5 hours	3 hours
Major findings	UAS enabled close-up imaging with enhanced visibility of concrete spalling on columns; computer vision image-based 3D reconstruction generated a high-fidelity 3D model of the bridge.	UAS successfully accessed spaces between girders and captured high-resolution images; defects located at midspan that are difficult to observe using conventional inspection methods were documented more effectively.	UAS-assisted inspection improved inspector safety by reducing exposure to live traffic; computer vision image-based 3D reconstruction enabled visualization, quantitative measurement, and digital documentation of girder deformation caused by vehicle impact.
Key challenges	Reduced 3D reconstruction quality in poorly illuminated and low-texture areas; challenging navigation in confined spaces beneath the bridge.	Flying between girders required precise maneuvering and increased pilot workload; obstacle avoidance functionality limited access to narrow spaces between girders.	Reduced reconstruction quality on featureless steel surfaces; challenges associated with UAS operation near active traffic.

CHAPTER 10: CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This report systematically reviewed state and federal implementation efforts and emerging academic research developments related to reality-mapping-driven bridge inspection using camera-equipped UAS, handheld 360-degree cameras, and consumer-grade cameras to assess their applicability for IDOT bridge inspection practices. Based on the findings summarized throughout this report, several key conclusions can be drawn:

- The digital inspection workflow can be broadly divided into four stages: data collection, data processing, visual inspection and analysis, and reporting. While substantial efforts have focused on enhancing data collection through UAS technologies, relatively little attention has been devoted to integrating the subsequent stages into an end-to-end digital inspection framework. As a result, many existing workflows still rely significantly on manual effort for data management, defect assessment, and report generation.

- Previous pilot studies have demonstrated that no single UAS platform is universally optimal for all bridge inspection scenarios and that platform selection should account for multiple operational and environmental factors. Factors such as UAS size, camera specifications, GNSS-denied operation, obstacle avoidance, and resistance to magnetic interference should be considered to accommodate the target inspection environments.

- An up-to-date understanding of data security and the regulatory landscape should inform UAS platform selection and data management. Currently, NDAA-compliant UAS requirements, the Blue UAS list, and the Green UAS certification framework provide important references for evaluating data security considerations in UAS platform selection.

- Camera-equipped UAS have demonstrated significant potential to improve the efficiency, accessibility, safety, and cost-effectiveness of bridge inspections, particularly for routine visual inspections where access is difficult. Similarly, 360-degree cameras demonstrate potential for improving speed and efficiency in remote visual inspection when cameras can be moved on foot (e.g., short-span bridges and culverts). Previous case studies consistently reported reductions in reliance on under-bridge inspection trucks (UBITs), lane closures, and other access-intensive methods, while improving access to difficult-to-reach structural areas and reducing inspector exposure to hazardous environments. Correspondingly, benefit–cost analyses conducted in previous studies, as well as in this report, indicate that reality-mapping-driven routine inspections can provide substantial economic advantages over conventional approaches.

- The applicability and benefits of camera-equipped UAS vary considerably depending on inspection type, bridge characteristics, and operational conditions. Routine inspections and bridge deck screening are generally well suited to camera-equipped UAS deployment, whereas fracture-critical, special, and in-depth inspections remain more dependent on conventional methods due to the need for close-up, hands-on evaluation. However, camera-equipped UAS can still be a supporting tool for improving defect localization, documentation, and situational awareness. Similarly, bridge characteristics such as accessibility, clearance, traffic conditions, structural complexity, and service beneath the bridge strongly influence the suitability and cost-effectiveness of UAS-assisted inspection. The primary advantage of camera-equipped UAS lies in their ability to access hard-to-reach areas safely and efficiently. In contrast, bridge components that are readily accessible can be inspected more cost-effectively using 360-degree cameras or conventional handheld cameras. Therefore, careful bridge selection and definition of inspection objectives are important to maximize the benefits of camera-equipped UAS deployment. To support practical implementation, this report further develops a bridge applicability rating and inventory-level prioritization framework to evaluate the suitability of UAS-based inspection across different bridge scenarios and to assist decision-making for camera-equipped UAS deployment.

- Inspection quality remains one of the most important considerations for practical implementation. Defect detectability depends heavily on imaging configurations, including standoff distance, camera specifications, illumination conditions, and environmental factors. Consequently, quality assurance procedures, including laboratory experiments, controlled field testing, mission planning, and image review, are important for ensuring reliable inspection outcomes.

- Current UAS-based bridge inspection practices rely primarily on manual data processing, interpretation, and report generation. However, advances in artificial intelligence, 3D reconstruction, and digital reporting technologies demonstrate opportunities to expand the role of camera-equipped UAS beyond image acquisition toward more integrated inspection workflows. Although these technologies show promise in improving inspection efficiency, scalability, and data use, many remain at an early stage of development and require further validation before widespread adoption in practical bridge inspection applications.

- Although UAS-based inspection provides significant advantages, multiple technical challenges remain, including GNSS-denied navigation, magnetic interference, wind effects, confined operational environments, image quality limitations, and difficulties in 3D reconstruction. These challenges highlight the importance of appropriate UAS platform selection, as different UAS platforms offer varying levels of capability in addressing these challenges. Platform selection should also consider data security requirements, for which the Blue UAS and Green UAS programs provide useful references. In addition, careful analysis of target bridge characteristics and comprehensive mission planning are important to ensure safe, reliable, and effective inspection operations. For particularly challenging environments, such as the interior of box girders, handheld cameras equipped with auxiliary lighting may provide a more practical and efficient solution than UAS because of their simplicity, maneuverability, and reduced operational risk.

- Different digital inspection technologies offer distinct advantages and are suitable for different inspection objectives. UAS-mounted consumer-grade digital cameras provide improved accessibility and enable close-range data collection in hard-to-reach areas. LiDAR systems generate more reliable and higher-quality point clouds, particularly in environments with limited visual texture. Thermal cameras can identify subsurface defects such as delamination that are not visible in consumer-grade digital images. 360-degree cameras can improve inspection efficiency and reduce data collection costs by capturing comprehensive visual information with fewer images. Therefore, selecting appropriate digital inspection technologies and sensor payloads based on the bridge characteristics, inspection objectives, and required data products is essential for achieving reliable and efficient inspections.

Overall, the findings indicate that at this stage, camera-equipped UAS should be considered a complementary tool rather than a universal replacement for conventional bridge inspection methods. Their greatest value lies in improving accessibility, efficiency, safety, and digital data collection while supporting inspectors in performing more informed and efficient evaluations.

RECOMMENDATIONS

Based on the findings summarized in this report, the following recommendations are proposed to support the effective implementation of UAS-assisted bridge inspection by IDOT:

- **Conduct comprehensive demonstrations across diverse environments in Illinois:** Although previous studies have demonstrated the feasibility of UAS-assisted bridge inspection, additional large-scale demonstrations covering representative Illinois bridge types, inspection requirements, traffic conditions, and environmental settings are recommended. Such demonstrations would provide practical insights into applicability, limitations, operational challenges, and cost-effectiveness under local conditions, supporting broader implementation decisions.

- **Develop standardized workflows and data management systems:** As UAS-based inspections generate large volumes of images, videos, point clouds, and reconstructed models, efficient data storage, management, and retrieval become increasingly important. Future efforts should consider developing centralized, browser-based platforms or digital management systems that enable efficient visualization, defect tracking, historical comparison, and integration with existing bridge management systems. Such platforms may improve the usability of collected inspection data and facilitate long-term condition monitoring.

- **Conduct comprehensive benefit–cost analysis:** Given the fast-changing manufacturing, supply-chain, and regulatory landscape, a more comprehensive benefit–cost analysis should be a priority for future studies. Such an analysis should account for up-to-date cost assumptions, evolving drone technologies, the latest regulatory changes, and more state- and agency-specific operational conditions.

- **Evaluate the cost-effectiveness and efficacy of different sensing technologies:** Different sensing technologies, including consumer-grade digital cameras, thermal cameras, LiDAR, and 360-degree cameras, exhibit distinct advantages and limitations depending on inspection targets and objectives. Future efforts should further investigate the suitability of different sensor configurations for specific bridge components, defect types, and inspection requirements to establish practical guidance for sensor selection. In particular, 360-degree cameras mounted on handheld poles or similar supports can enable inspectors to rapidly and efficiently capture visual data while walking around accessible bridge areas. This technology has not been extensively explored and should be considered as a promising tool for rapid data collection in conjunction with camera-equipped UAS.

- **Develop and validate standardized guidance for bridge selection and deployment strategies:** Because the applicability and benefits of camera-equipped UAS vary substantially across bridge types and inspection scenarios, future implementation should prioritize bridges where camera-equipped UAS can provide the greatest advantages in accessibility, safety, efficiency, and cost reduction. The bridge selection and applicability rating framework developed in this report may serve as an initial basis for supporting deployment decisions. However, the proposed parameters are preliminary and require further validation through field demonstrations and practical implementation so that parameter selection can be refined and framework reliability can be improved.

- **Initiate research to develop and implement a digital bridge management framework:** There is an opportunity for IDOT to establish a digital bridge inventory and assessment program as a high-value, practical enhancement to existing bridge inspection and asset-management workflows. The program should be designed around a simple aspirational principle: (over time) establish a digital record of the entire IDOT bridge inventory and employ it for efficient assessment and decision-making. In this new paradigm, all bridges would have an established digital baseline that would serve as a reference point for future evaluations and actions. Operationally, this means using appropriate digital reality-capture tools across the spectrum of bridges in the IDOT inventory, such that the chosen technology provides clear value in safety, access, cost, documentation, and future decision-making.

  The greatest return on new investment is expected for major bridges and other high-cost inspection scenarios, such as large river crossings, high-clearance structures, complex interchanges, long-span or geometrically complex bridges, and bridges where conventional inspection requires substantial lane closures, under-bridge inspection trucks, rope access, extended field time, or difficult access planning. For these structures, camera-equipped UAS, 3D reality capture, thermal imaging, LiDAR, and related tools can create reusable digital condition records that support inspection planning, documentation, repair scoping, maintenance decisions, and comparison across inspection cycles.

  For more standard bridges, the same framework can still guide the use of lower-cost tools, some of which are already owned by IDOT (e.g., terrestrial LiDAR). In addition to terrestrial LiDAR, pole-mounted 360-degree cameras, handheld cameras, or small UAS provide opportunities to efficiently capture and evaluate bridge conditions. These tools provide the basis for establishing a consistent longitudinal record of a bridge over its lifespan and generally improve visibility, reduce ladder use, document hard-to-reach details, and avoid repetitive site visits—compared to current practice inspection methods. In this way, the digital documentation program would function as a cost-conscious platform-selection approach that guides IDOT in choosing the right tool for the right bridge, rather than treating any single technology as universally applicable.

The proposed program should also preserve the role of conventional hands-on inspection where it is required and appropriate. In particular, UAS and other remote imaging tools should not be positioned as replacements for fracture-critical, non-redundant, special, or in-depth inspections that require arm's-length access and direct inspector judgment; instead, they can support those activities through pre-inspection planning, improved visual documentation, access assessment, and post-inspection records where appropriate. A secure digital condition archive should be integrated with IDOT's existing asset-management platforms, including the Illinois Highway Information System (IHIS), AASHTOWare for load ratings, BridgeWatch, and other relevant systems, so that visual records, 3D models, NDE results, field notes, repair histories, and inspection documentation can be accessed as part of day-to-day operations. While the findings of this project showed that transportation agencies have examined individual parts of this workflow, such as UAS data collection, 3D modeling, and digital documentation, there remains a need for a unified, IDOT-specific framework that identifies the bridge classes and inspection scenarios in which these tools deliver the strongest return on investment. Such a program could reduce unnecessary access-equipment use, traffic-control setups, repeat site visits, and scattered inspection records while improving inspector safety, public safety, continuity of condition documentation, and the speed and confidence of maintenance and operational decisions. Over time, this living digital condition archive would help IDOT lower life-cycle inspection and maintenance costs while making better-informed decisions across its extensive bridge inventory.

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APPENDIX A: EFFICIENCY ESTIMATION

1. Under-Bridge Inspection Truck (UBIT)

- Assume 8 hours to complete both superstructure and substructure inspection.
- Total inspection time ≈ 8 h (1 day)

2. Camera-Equipped UAS (Manual)

Assumptions:

- Considering maneuvering time and manual adjustments during inspection, assume an effective inspection speed = 0.2 m/s.

Girder inspection:

- Total inspection length = 12 girders × 4 faces/girder (including deck bottom) × 6 spans × 20 m/span = 5760 m
- Girder inspection time = 5760 m / 0.2 m/s = 28,800 s ≈ 8 h

Column inspection:

- Total inspection length = 25 columns × 4 faces/column × 10 m/face + 2 abutments × 12 m (width) × 10 m (height) / 2 m (height of each image) = 1120 m
- Including 0.5 h transition time, total column inspection time ≈ 0.5 h + 1120 m / 0.2 m/s ≈ 2 h

Additional time:

- Inspection of bearings and miscellaneous components ≈ 1 h
- Backup/redundancy allowance ≈ 1 h

Total:

- Estimated total inspection time ≈ 8 h + 2 h + 1 h + 1 h = 12 h (~2 working days)

3. Camera-Equipped UAS (Autonomous)

Assumptions:

- Assume inspection speed = 0.5 m/s due to autonomous flight capability and reduced pilot workload.

Girder inspection:

- Total inspection length = 12 girders × 4 faces/girder × 6 spans × 20 m/span = 5760 m
- Girder inspection time = 5760 m / 0.5 m/s = 11,520 s ≈ 3.2 h

Column inspection:

- Total inspection length = 25 columns × 4 faces/column × 10 m/face + 2 abutments × 12 m (width) × 10 m (height) / 2 m (height of each image) = 1120 m
- Including 0.3 h transition time, total column inspection time ≈ 0.3 h + 1120 m / 0.5 m/s ≈ 1 h

Additional time:

- Inspection of bearings and miscellaneous structures ≈ 1 h
- Backup/redundancy allowance ≈ 1 h

Total:

- Estimated total inspection time ≈ 3.2 h + 1 h + 1 h + 1 h = 6.2 h (~1 working day)

4. LiDAR-Equipped UAS

Assumptions:

- Assume inspection speed = 0.5 m/s
- Similar inspection workflow as autonomous camera-equipped UAS

Total:

- Estimated total inspection time ≈ 6 h (~1 working day)

5. Terrestrial Laser Scanning (TLS)

Assumptions:

- One scanning station every 10 m
- Three rows of stations along bridge width → 36 stations
- Additional 2 stations/span for columns → 12 stations

Total stations:

- 48 stations

Scanning time:

- Assume 15 min/station

Total:

- Estimated inspection time ≈ 48 × 15 min = 720 min ≈ 12 h (~2 working days)

6. 360-degree Camera Inspection

Assumptions:

- Same station distribution as TLS → 48 stations
- Assume 3 min/station

Total:

- Total inspection time ≈ 48 × 3 min = 144 min ≈ 2.5 h
- Considering setup and movement between stations, estimated total inspection time ≈ 3 h

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