

DEVELOPMENT OF AN INTEGRATED UNMANNED AERIAL SYSTEM (UAS) VALIDATION CENTER



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Abstract

Unmanned Aerial Systems (UAS) have the potential to drastically change how civil infrastructure is inspected, monitored, and managed. This innovative technology can ensure the inspector's safety, provide additional inspection information, and reduce costs. However, a challenge arose as this industry expanded: a lack of standardized guidelines or minimum performance requirements to perform these operations. With no standard tests to verify UAS' ability to conduct inspections and unknown detection capabilities, agencies are left to rely upon consultants' or vendors' promotional material and claims when considering UAS deployment. The following pooled fund project proposes a series of performance-based assessments and procedural documentation to establish minimum standards for using UAS in bridge inspection applications. Through this work, the following performance-based tests have been developed: (1) a controlled environment simulating bridge geometries to assess the overall capability of a UAS used for bridge inspection [evaluation chamber], (2) an assessment of UAS performance under multiple environmental temperatures [environmental temperature chamber], (3) a UAS performance assessment under varying wind speeds [wind chamber], (4) a consolidated checklist compiling Federal Aviation Administration guidelines and best practices [flight checklist], and (5) a field assessment of UAS under conditions analogous to on-site bridge inspection [practical test]. For infrastructure owners, embracing these performance-based assessments will help ensure that UAS meets a minimum level of performance and allow owners to verify and distinguish between various UAS used for bridge inspection. This work also discusses positive feedback from beta testing provided by industry and infrastructure owner representatives, showcasing the effectiveness of providing an authentic assessment of UAS bridge inspection capabilities. Future work encourages the wide implementation of this assessment program and encourages owners to refrain from using untested technology in the inspection of their infrastructure.

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1. INTRODUCTION

1.1 Importance of Bridge Inspections

Inspection is essential in a moving society to maintain infrastructure investments. Timely inspection prevents catastrophic accidents caused by damages from poor design, natural hazards, or aging infrastructure. Besides safeguarding users, studies show regular inspections are more cost-effective than replacing structures (Ilbeigi & Pawar, 2020). Moreover, inspections can notify stakeholders of potential problems early on, prompting preventive measures to safeguard the public and protect the investment. Adequate inspections have the potential to benefit society and support economic growth.

1.1.1 Bridge Inspection in the U.S.

In the United States, while each state builds and maintains public bridges according to standards, the Code of Federal Regulations mandates inspections at regular intervals not to exceed 2 years by Section 2.3 of the AASHTO manual (AASHTO, 2019). Depending on the bridge's classification, determined during its design or service life, some may require more frequent inspections. Conversely, others might need extensive inspections spanning several months, incurring higher costs, and necessitating specialized personnel and equipment.

1.2 Types of Bridge Inspections

This document categorizes bridge inspections based on the level of detail and inspection frequency.

1.2.1 Routine Inspections

Routine inspections, as defined by the Code of Federal Regulations, are performed on bridges inspected at regular intervals not to exceed the interval established using one of the risk-based methods described in §650.311 (LII, n.d.c). A report detailing the condition of key bridge components like piers, deck, and superstructure is required. These inspections involve a general evaluation of the structure, with reporting intervals ranging from 12 to 48 months, contingent on the bridge's type, condition, traffic, location, and age. The primary objective of routine inspections is to identify defects in the infrastructure, recommending further assessment and necessary maintenance. Routine inspections are the most prevalent type of inspection in the U.S., encompassing most of the bridge inventory.

1.2.2 Non-Redundant Steel Tension Member (NSTM) Inspections

A non-redundant steel tension member (NSTM) inspection, previously known as fracture critical inspection, is a more detailed assessment than a routine inspection. It mandates hands-on inspection within

arm's length of the member using visual techniques, sometimes complemented with nondestructive evaluation. This rigorous standard is due to the nature of NSTM members in bridges—a primary steel member fully or partially in tension and without load path redundancy whose failure may cause a portion of or the entire bridge to collapse (LII, n.d.b). Conducting NSTM inspections often necessitates specialized equipment to ensure access within arm's length to all parts of the structure. Inspection intervals can range from 12, 24, or 48 months (CFR, n.d.).

1.2.3 Damage Inspections

Damage inspections are triggered by natural hazards or accidents that damage or potentially compromise a bridge's integrity. They can also be called in-depth or special inspections in the Code of Federal Regulations (CFR, n.d.). Conducted on an as-needed basis, these inspections often require specialized equipment to ensure the structure's integrity after the incident and the safety of its users.

1.3 Traditional Bridge Inspection Techniques

Bridge inspection employs a range of techniques to directly or indirectly assess the condition of the infrastructure. Based on their impact on the structure post-inspection, there are two types: destructive and non-destructive.

1.3.1 Destructive Testing

Destructive testing involves intrusive methods to gather information about a structure's integrity. Typically, this means extracting a portion of the structure for analysis, applying foreign procedures in situ, or intentionally damaging parts of the structure to study its behavior or properties (Limble CMMS, n.d.). From common compression testing in concrete cylinders to corrosion testing in steel members, destructive testing can provide a detailed analysis of the physical properties of the tested items.

1.3.2 Nondestructive Testing

Nondestructive testing aids in inspecting structures without causing permanent damage or disrupting their service. The most common method is visual inspection, relying on an inspector's expertise to assess the structure (Dwivedi et al., 2018). These inspectors, trained professionals, often work near the structure. They sometimes need equipment like ladders, bucket lift trucks, boats, or scaffolding to access specific areas, necessitating additional skills, and exposing themselves to potential risks. Recently, industry has introduced drones as a valuable tool to help inspectors in their tasks by safely approaching hard-to-reach areas of structures.

1.4 Evolution of Unmanned Aircraft Systems (UAS) in Bridge Inspections

Unmanned aircraft systems (UAS), also known as Uncrewed Aircraft Systems or drones, operate without an onboard pilot to complete basic operations to take off, hover, fly, and land. The UAS market has surged in the past decade due to many emerging applications. Ranging from search and rescue, mapping, surveying, digital twin development, and inspection, the market offers a variety of UAS tailored to clients' needs (Barnhart et al., 2016). A UAS comprehends not only the unmanned aerial vehicle (UAV) itself but also the associated support equipment, control system, and human operators necessary for safe and efficient operation.

1.4.1 UAS Applications in Bridge Inspection

UAS, widely available in the market, serves diverse purposes. Their affordability ranges from \$200 models for recreation to \$2,000 for surveying and mapping. These drones are portable, with some having a diagonal distance of just 12 inches and weighing as little as 5 pounds. They are user-friendly, have intuitive controls and freely accessible learning resources. Given the proper training and safety measures, UAS can operate indoors and outdoors. With these advantages, they have gained significant traction in sectors of the bridge inspection industry (Seo et al., 2018).

1.4.2 Technology Capabilities Applied to Bridge Inspection

UAS offers bridge inspectors solutions in safety, record-keeping, and cost-effectiveness. UAS can access remote areas that, during traditional inspections, require equipment elevating inspectors off the ground or above water (e.g., snooper). Eliminating the need for such equipment reduces temporary loads on structures. UAS also provides a historical record of the structure. By consistently gathering data, future inspectors can compare current conditions to records, identifying defects that may have been previously overlooked. Moreover, UAS can cut inspection costs by eliminating the need for heavy equipment rentals or purchases, reducing personnel, and streamlining data post-processing.

Furthermore, technological advancements have equipped UAS with new capabilities that were only possible on the ground, using heavy equipment such as thermal imaging, LiDAR data collection, 3D reconstruction, post-disaster reconnaissance, and tracking displacements and settlements over time. The "S" in UAS, representing system, highlights its ability to easily replace sensors according to user needs and adapt to evolving market innovations.

1.5 Regulations and Standards in the UAS Market in Bridge Inspection

The UAS market has witnessed a surge in usage, production, and innovation but lacks comprehensive regulation (Huang et al., 2021). The following sections explore the limited regulations existing in the global market.

1.5.1 UAS Regulations and Standards: Outside the U.S.

UAS technology has evolved in multiple markets worldwide, dominated by China, the United States, Switzerland, France, Israel, and Taiwan. As such, regulations and standards governing the use of UAS for infrastructure outside the United States vary by country, with each nation having its own regulatory body overseeing aviation. For example, the European Union has the European Union Aviation Safety Agency (EASA), which issued a set of regulations effective from 2020 that categorizes UAS operations into "open," "specific," and "certified" categories, each with its own set of rules and requirements (EASA, n.d.a). Similarly, Canada's Transport Canada has established safety rules for drone flight in their country (Transport Canada, n.d.). In Australia, the Civil Aviation Safety Authority (CASA) oversees UAS operations and has regulations and requirements (CASA, n.d.). Despite the varying specifics from one nation to another, common themes across many regulations include the need for operator training or certification, the importance of keeping the UAS within visual line of sight, restrictions on night flights, and mandates to avoid other aircraft and populated areas. Additionally, many countries participate in the International Civil Aviation Organization (ICAO), which provides standards and recommended practices. However, adopting and implementing these recommendations vary by country (ICAO, n.d.). Furthermore, none of these organizations enforce regulations when UAS are used to inspect infrastructure.

1.5.2 UAS Regulations and Standards: In the U.S.

While some organizations have established their procedures for purchasing UAS in the United States, many entities base their decisions on vendor sales pitches demonstrating select aircraft capabilities. A comprehensive literature review performed by Capa Salinas (2021) and updated in this document reveals that there are no comprehensive regulations, standards, or tests specifically for UAS used in structure inspections, surveying, mapping, aerial photography, and other engineering applications (Capa Salinas, 2021). Without federal or state regulation, agencies often face the challenge of choosing among high-priced aircraft based on vendor claims alone. In this largely unregulated market, infrastructure inspection's safety, reliability, and effectiveness are not guaranteed, potentially jeopardizing public safety.

1.6 Motivation for this Study

This study presents the development of a UAS Validation Center dedicated to evaluating UAS for infrastructure inspection, emphasizing bridges and similar structures. The following project proposes the application of performance testing, offering standardized methods and procedures to assess UAS inspection capabilities. It aims to assess these capabilities in both controlled environments and real-world scenarios. This project aims to provide agencies with critical information regarding UAS inspection abilities, aiding in well-informed purchasing and operational decisions.

1.7 Research Objectives

This research establishes the standards, protocols, and testing requirements that a specific unmanned aircraft system (UAS) must meet and demonstrate for a particular application. The specific objectives are as follows.

- Define and categorize the constraints and requirements a UAS must adhere to for different civil engineering tasks, specifically focusing on bridge inspections.
- Investigate the various environmental and structural challenges, such as constrained locations, and develop a framework to map UAS capabilities to these challenges in a confined environment.
- Develop a systematic testing methodology to ascertain whether a UAS adheres to the predefined criteria for different civil engineering applications, specifically focusing on bridge inspections.
- Propose a validation framework that assesses the UAS as a whole system in real-world scenarios in bridge inspection.
- Create validation criteria that can serve as a reference for agencies and other stakeholders when assessing UAS suitability for specific civil engineering applications.
- Refine the performance measures and validation criteria based on stakeholder feedback to ensure broad acceptability and applicability.

2. PRIOR RESEARCH AND BACKGROUND

2.1 UAS in Bridge Inspection

UAS has gained significant traction in the infrastructure market, particularly bridge inspection. Their usage in this sector has notably risen recently (Simic Milas et al., 2018). Routinely, UAS captures visual data in standard formats like JPEG or TIFF, accesses elements elevated off the ground and covers distances far from easily reachable spots. They have also introduced novel applications: mapping without a total station, aerial photography without crewed aircraft such as helicopters, and thermography without positioning an operator near the inspection target. Such a range of applications has piqued the interest of the private and public sectors and has made the technology attractive to the bridge inspection industry.

UAS inspections are becoming more popular not only for their affordability but also for their effectiveness. A comparison between UAS-assisted bridge inspections and traditional hands-on inspections was performed to evaluate performance in visual inspection of steel bridge members at the S-BRITE facility at Purdue University. The findings revealed that both methods have similar levels of variability in performance, suggesting that human factors play a significant role in inspection outcomes, irrespective of the method used. The author provided recommendations to improve visual inspection consistency for both inspection methods. Specific suggestions for UAS-assisted inspections were categorized into three areas: inspection equipment and environment, inspector training, and inspection procedures (Campbell, 2019).

2.2 Use of UAS by State Departments of Transportation

Transportation agencies in the United States widely utilize drones. Out of 48 state Departments of Transportation (DOT), 45 have employed UAS in at least one highway construction project, according to a survey reported in a National Cooperative Highway Research Program report (NCHRP) (Turkan et al., 2022). The report indicates that the primary applications of this technology are aerial surveying, work progress monitoring, and stockpile measurement. The study outlines current usage while highlighting potential benefits, challenges, and areas where more information is needed.

DOTs have found many applications for UAS. Pennsylvania DOT employs UAS to survey road conditions, determine maintenance needs, inspect bridges, and monitor changes in terrains that might impact highways (Tran et al., 2022). States like New York and Utah have harnessed UAS in construction for years. For instance, Utah DOT formalized its UAS construction program in 2016, leading to increased cost efficiency, data quality, and worker safety (Harper et al., 2019). In contrast, using drones, a consultant in New York evaluated 1,000 wheelchair ramps in 3 hours, while the traditional approach took 3 years for 8,000 ramps (Harper et al., 2019). Meanwhile, Washington State DOT utilizes UAS for flood monitoring, collecting data in various formats to address emerging flood-related concerns (Park et al., 2021). This, along with many other uses, shows how DOTs have incorporated this technology into their daily activities.

2.3 Existing Tests and Evaluation of UAS Used in Bridge Inspections

The following section summarizes existing requirements for UAS by international and domestic governing agencies related to bridge inspection and highlights the gaps in existing literature.

2.3.1 Review of Tests Related to UAS Bridge Inspection

Salaan et al. (2018) highlighted the Japanese government's requirements for bridge inspection robots under the Next Generation Robots for Social Infrastructure (NGRSI) (Salaan et al., 2018). These robots must be able to evaluate bridge damage, eliminate the need for scaffolding, and ensure safe operations. Optionally, inspect complex bridge parts, reduce reliance on ladders or trucks, adjust to the lighting, provide detailed inspection summaries, and be universally applicable across bridge types. Although many requirements have been addressed in the literature, others remain uncertain and cannot be approved in this industry.

Research from the Netherlands has explored UAVs for structural inspections, but comprehensive guidelines are still lacking. In 2020, the Dutch aviation authority released a risk analysis for self-flying drones in populated areas (EASA, n.d.b). While there is extensive literature on UAV systems, including their history, functionalities, and safety, there is a lack of material on the parameters UAS must meet for close proximity structural evaluations and related regulations. Experiments have been done in various settings, from randomized box arrangements (Scherer et al., 2007) to open environments near buildings (Mashaly et al., 2016). However, a standard testing framework remains undefined, especially for bridge inspections.

Researchers are working on The National Cooperative Highway Research Program (NCHRP) 12-122 project, focusing on the potential of UAS for highway bridge inspections. This study establishes guidelines on how DOTs can utilize UAS for bridge inspections. The research will particularly explore the capability of UAS to collect data in line with the *AASHTO Manual for Bridge Element Inspection (MBEI) Methodology* (AASHTO, 2019). The final goal is to write AASHTO guidelines to aid state DOTs in using UAS technology to inspect and evaluate bridge elements. The research was completed in 2023; the final report is expected in 2024 (TRB, 2023).

2.3.2 ASTM Specifications

In the U.S., the American Society for Testing and Materials (ASTM) once endorsed the *Standard Specification for Design and Performance of an Airborne Sense-and-Avoid System* under the F38 Committee 2007 (ASTM, 2007). This standard, which dealt with detecting airborne objects and ensuring safe distances, was withdrawn in 2014 due to its perceived irrelevance to the evolving industry (ASTM, n.d.). Although Committee F38 has formulated 25 active ASTM standards concerning UAS topics, such as assembly and design parameters, they lack guidance on beyond visual line-of-sight operations, UAS performance, training, and, notably, standards for UAS inspections.

Similarly, ASTM Committee E54 has issued 18 standards focused on homeland security applications,

encompassing protection protocols during natural disasters and responses to varied threats, including chemical and explosive detection. Some of these standards relate to emergency response robots, including those with flight capabilities akin to UAS. Moreover, while a few of the standards by Committee E54 touch upon visual line-of-sight (ASTM, 2021) and visual acuity (ASTM, 2017), none specifically address UAS or their inspection protocols.

2.4 Performance-Based Assessments in Engineering

2.4.1 Performance-Based Concept

Performance-based is a relatively new term in engineering, and interest in civil engineering is increasing. In the past, most designs and analyses followed a code or standard generally assumed to work for every case. A performance-based approach focuses on explicitly defining the objectives and performance criteria for design or analysis. In other words, performance-based focuses on the end rather than the means. Performance-based design of structures formally began in the building world with seismic recommendations after the 1994 Northridge earthquake (SEAOC, 1995) and has been slowly adopted in other areas such as highway transportation, water structures design, bridge design, pavement design, and many more (Easa & Yan, 2019).

2.4.2 Performance-Based Assessment

In engineering education, performance-based education is a teaching and learning methodology measuring individual performance at different levels given predefined objectives or outcomes. Its origin in education comes from the graduate attributes adopted by the international agreement in the Washington Accords, which incorporate the development of outcomes-based accreditation criteria in the education of professional engineers in all engineering disciplines (Anwar & Richards, 2015). The adoption of the accord in the United States is represented by the Accreditation Board for Engineering and Technology (ABET) since its implementation in 1989 (International Engineering Alliance, n.d.). ABET recommends applying performance-based assessment using predetermined objectives or outcomes to assess a person's knowledge, skills, or competencies.

2.4.3 Certifications in the Civil Engineering Field

Civil engineers are not foreign to tests, evaluations, and certifications. Most engineers are familiar with the Fundamentals of Engineering exam as the first step toward licensure, followed by professional experience, the Principles and Practice of Engineering exam, and other assessments established by regulatory bodies (NCEES, 2024). Some professionals will choose different paths in our profession where they will encounter

specific certifications. Examples from multiple fields are presented below.

Some professionals will be required to obtain a certification from the Society of Professional Rope Access Technicians (SPRAT) if they will be conducting rope access operations. SPRAT certifications require attending a certification session and passing a written test, verbal test, and hands-on physical performance-based test (SPRAT, n.d.). Others will be working on bridge inspection where the Code of Federal Regulations mandates, among other requirements, to complete a Federal Highway Administration-approved comprehensive bridge inspection training course. The training includes field exercises, curriculum on the AASHTO element level condition, and assessments (NHI, n.d.). Other certifications where professionals have become familiar with being assessed are Leadership in Energy and Environmental Design (LEED) for people working in the field of green building practices and standards (U.S. Green Building Council, n.d.), American Concrete Institute (ACI) certifications on concrete testing (ACI, n.d.), The Occupational Safety and Health Administration (OSHA) safety training (OSHA, 2024), among others.

2.4.4 Performance-Based Assessments

The following document is divided as follows. In Chapter 3, the author presents the refined UAS evaluation chamber, a performance-based assessment that mimics the complex geometries of the U.S. bridge inventory and resembles inspection experiences. Chapter 4 introduces a grading procedure for the UAS evaluation chamber, using quantitative and qualitative performance-based outcomes and introducing certification levels. Chapter 5 presents a performance-based assessment of UAS under different environmental temperatures to account for the variability within states and seasons. Chapter 6 presents a performance-based assessment of UAS under variable wind following the experience of UAS pilots when working in outdoor environments. Chapter 7 introduces a flight checklist for best practices when performing UAS inspection operations based on literature recommendations and the author's experiences. Chapter 8 shares results from beta-testing conducted in the designed and built prototypes of the performance-based assessments presented in Chapters 3–7. The report ends with concluding remarks and ideas for future work. Appendix A has been written in commentary language to explain further some design decisions in developing these assessments. These considerations can be helpful when this project is implemented or in future revisions.

3. DEVELOPMENT OF A UAS EVALUATION CHAMBER TEST FOR BRIDGE INSPECTION

The evaluation chamber for bridge inspection is a test method intended for small, unmanned aircraft

systems (UAS) that comply with the following requirements.

- Weight requirements presented in Part 107 of the Code of Federal Regulations (14 C.F.R. §107.3): small UAV weighing less than 55 pounds (on takeoff) (LII, n.d.a).
- Horizontal requirements with a propeller-tip-to-propeller-tip distance less than or equal to 2.5 feet. UAVs within 2.5 feet and 3 feet 4 inches can be tested inside the chamber cautiously, and protective equipment is recommended.

The UAS evaluation chamber test considerations are presented in the following pages.

3.1 Concept and Objectives

The UAS Evaluation Chamber is a validation criterion for inspection of civil engineering structures using UAS to provide performance-based testing focusing on bridge inspection. The evaluation chamber is designed to resemble typical inspection conditions and accommodate commonly available UAS used for bridge inspection. The evaluation chamber objectives are as follows.

- Develop a repeatable test a UAS must complete to qualify before inspecting civil engineering structures.
- Establish an environment for the test based on constraints and challenges when conducting bridge inspections.
- Assess UAS inspection capabilities based on identifying steel and concrete defects inside the environment developed for the test.

3.1.1 Overview of the Test

The evaluation chamber is designed to fit most UAS dimensions commonly used in bridge inspection and incorporate elements resembling bridge structures' components. The chamber is allocated in a 40-foot standard cargo container (width of 8 feet and height of 8 feet 6 inches), providing an environment where weather conditions do not affect the execution of the test, such as wind, lighting, precipitation, and temperature changes. In addition, the chamber inhibits GPS signals to allow pilots to test their navigation skills in typical environments where Global Navigation Satellite Systems (GNSS) signals are limited, e.g., under structural elements.

The evaluation chamber is presented in Figure 3.1. The chamber is engineered to evaluate the UAS's proficiency in identifying and reporting steel and concrete defects within a controlled environment that mimics bridge settings. Within the chamber, defects are embedded in steel and concrete specimens, as well as in visual components. These components are crafted to mirror bridge geometries and replicate typical bridge inspection scenarios. Supplemental lighting ensures clear visibility of all specimens and components.

The test starts at the chamber's entrance. The pilot is prohibited from entering the chamber during the test.

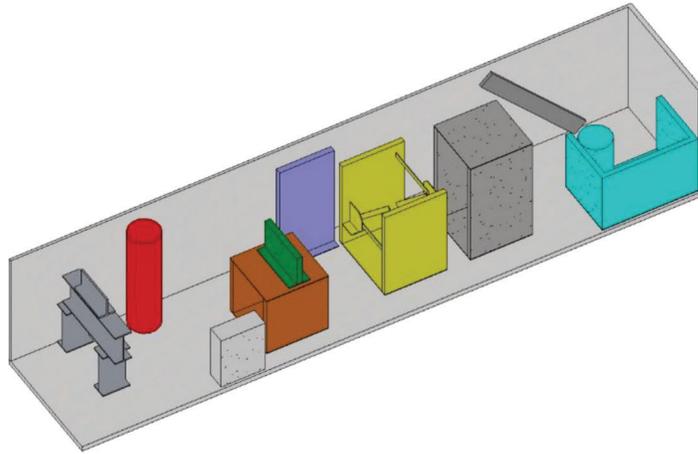


Figure 3.1 Evaluation chamber for bridge inspection.

It concludes once the UAS has gathered sufficient data to comprehensively assess the chamber’s findings.

3.2 A Review of UAS Used in Bridge Inspection

Two significant constraints impact UAS when flying near objects, the overall horizontal size of the UAV and the relative distance from the UAV to the nearby objects. Studies emphasized that the turbulence generated can notably influence the data quality collected as UAVs approach objects. These considerations became relevant in determining the dimensions of the test area and the size of UAVs suitable for evaluations.

This research evaluated the sizes of UAVs commonly used in bridge inspections. It was found that most UAVs used for these inspections have a diameter of fewer than 2.5 feet. In addition, the study assessed the impact of proximity effects, such as “ground effects” and “ceiling effects,” which are linked to the interaction of the propellers with surrounding surfaces. The study assessed safe distances around UAVs and concluded that for the design of the evaluation chamber, a UAV’s typical maximum size should be 2.5 feet in diameter, with a clearance distance of 10 inches to 12 inches. As a result, a design distance of 3 feet 4 inches to 3 feet 6 inches.

In this section, the UAV’s typical maximum size of 2.5 feet in diameter is reviewed and verified to ascertain that the proposed parameters remain valid and compliant with present UAS platforms.

3.2.1 UAS Platforms Used in Bridge Inspection

A comprehensive literature review was conducted to identify all the UAS platforms registered and allowed to fly in the United States. A key component is Remote ID, a requirement enforced by the FAA for all manufacturers to make their UAS trackable. Fifty-six platforms have been registered in the FAA with Remote ID compliance, but only 53 are considered small UAS—weight between 0.55 and 55 lbs. inclusive. From those UAS, 37 are documented for infrastructure

applications, including bridge inspection. A comparison between the drones provided in an initial study (2021) and now (2024) shows how UAS are not increasing in size and, in some cases, decreasing. Figure 3.2 summarizes the 37 platforms with dimensions in inches.

From the data provided, it is evident that the vast majority, approximately 86%, of UAS utilized in infrastructure applications have dimensions less than 2.5 feet out-to-out (highlighted by the red dashed line in Figure 3.2), and 97% have dimensions less than 3.0 feet (the maximum recommended distance from the original study. Notably, only one UAV, the RangePro 1100, falls between 2.5 and 3.0 feet. Upon excluding the larger UAVs, the data suggests that a size of 2.5 feet effectively encompasses nearly all UAS platforms currently employed in the infrastructure market. Therefore, 2.5 feet has been verified as the representative dimension for a typical UAS, and a design distance of 3 feet 4 inches to 3 feet 6 inches remains adequate.

3.3 Evaluation Chamber Research Gaps and Scope

The UAS Evaluation Chamber’s considerations omit specific guidelines not considered in the study and require further investigation. The aviation and structural international regulatory bodies have not provided standards or specifications to govern UAS inspections. The U.S. market is continuously growing, and some types of assessments are needed to guarantee the quality and availability of this type of inspection. The following work presents a compendium of performance-based assessments to govern UAS inspections and evaluate and certify inspectors using this technology. The performance-based assessments have been developed based on the U.S. bridge inventory, the growing UAS market, and current inspection procedures.

3.4 Special Considerations for the UAS Evaluation Chamber Test

The following updates are presented after identifying special considerations of the evaluation chamber.

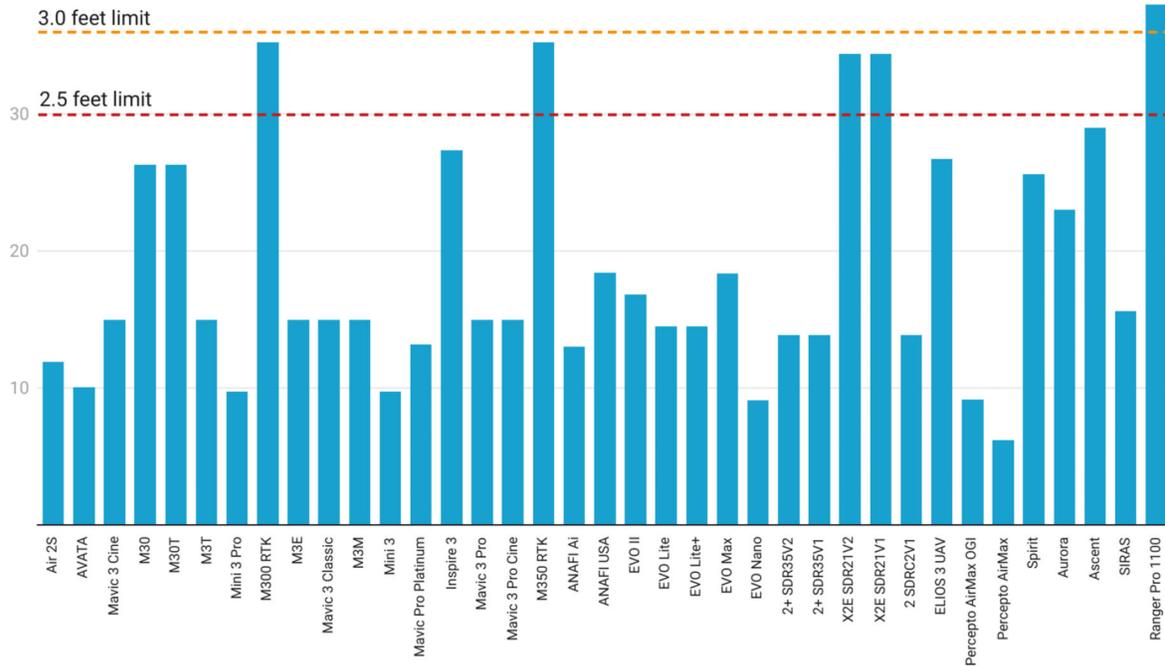


Figure 3.2 Diagonal dimensions of UAS platforms used in infrastructure (in inches).

3.4.1 Addition and Identification of Steel and Concrete Specimens

The evaluation chamber incorporates a mix of image-based components along with steel and concrete specimens. While the original chamber did have steel and concrete elements positioned to mimic real-life bridge inspection scenarios, these were not distinctly marked in the chamber’s drawings and analyses. Moreover, while the original study details some inspection experiences within the chamber’s components, including “actual” specimens that exhibit those defects are essential. As a result, 15 steel and one concrete specimen have been integrated into the evaluation chamber. Section 3.5 revisits the original chamber components and introduces these new steel and concrete specimens.

3.4.2 Updates to the Image Inventory

The initial image inventory comprised high-resolution photos of steel and concrete defects from various member locations, presented with a measuring tape for scale during the processing and printing phase. Nevertheless, these images were already adjusted to the proper scale and do not require an object for scale. Some original images also included multiple shots of the same element from different angles for evaluation during beta testing. These redundant images have been reviewed, with only the best ones retained in the updated inventory. Thus, the revised inventory includes new images meeting these refined criteria and updates existing ones by eliminating the scaling aid and removing any redundant images.

3.4.3 Assessment Method for the Evaluation Chamber

The final deliverable from the evaluation chamber test is an element-level inspection report detailing key observations made during the test. This report offers an unbiased means of gauging the UAS’ inspection capabilities within a controlled environment reflective of typical field conditions. While the original study did not include a method to authenticate the report, it suggested a potential grading system for attaining certification. Building upon these recommendations, the author proposes a grading scheme that takes into account the following factors.

- The grading scheme must be objective, ensuring consistency and repeatability across different proctors or graders.
- It should allow for flexibility when elements within the chamber undergo modifications.
- Prior to its official adoption, the grading scheme must undergo validation through beta testing.
- Uniformity in grading should be maintained throughout the entire evaluation chamber.

Based on the post-test inspection report, an analytic rubric is chosen to grade and determine certification levels. This rubric encompasses the chamber’s four elements: steel and concrete elements, components, and resolution charts. The rubric will provide clear grading guidelines based on defect reporting accuracy, provisions for adjustments if chamber elements change, and sets certification levels based on demonstrated expertise in the evaluation chamber. The final assessment method is presented in Chapter 4.

3.4.4 Testing Certification Levels

Certification levels indicate the UAS’s capabilities according to minimum criteria. These levels connect the proficiency displayed during the test with the competency to conduct UAS inspections in real-world scenarios. The designated certification levels for the evaluation chamber demonstrate incremental capabilities from Level A, Level AA, and Level AAA.

3.5 Components and Elements of the Modified UAS Evaluation Chamber

The components and elements in the modified UAS evaluation chamber are presented below.

3.5.1 Components Inside the Evaluation Chamber

3.5.1.1 Component 1. Component 1, depicted in Figure 3.3, evaluates the UAS’ response when approaching elements from above, a scenario frequently encountered in deck inspections. This is particularly relevant when dealing with vertically oriented surfaces or navigating confined spaces. The component measures 3 feet 6 inches in width, 2 feet in height, and has a depth of 4.5 inches.

3.5.1.2 Component 2. Component 2, shown in Figure 3.4, represents tall and slender aspects commonly found

in bridge elements like piers, walls, girders, and other vertical structures in open settings. This component is designed to examine ground and ceiling effects while featuring two tall faces where defects can be identified. It measures 3 feet 6 inches in width, 7 feet in height, and has a depth of 4.5 inches.

3.5.1.3 Component 3. Component 3, illustrated in Figure 3.5, is designed to emulate cylindrical structures’ shape, slenderness, and height with round surfaces. Due to its shape, the UAV must capture multiple images from various angles, both horizontally and vertically, to ensure a thorough component assessment. This component is strategically positioned so the UAV cannot access its entire face, thus preventing a 360° evaluation. Placing it against a container wall obscures certain areas, presenting challenges for the UAS. The component has a diameter of 2 feet and stands 7 feet tall.

3.5.1.4 Component 4. Component 4, depicted in Figure 3.6, is designed to assess scenarios where the UAS needs to view an object from below, akin to looking upward. This component simulates a confined passage reminiscent of the inside of a box girder. Its dimensions are an internal width of 3 feet 4 inches, an external width of 4 feet, and a height and depth measuring 4 feet.

3.5.1.5 Component 5. Component 5, as illustrated in Figure 3.7 and Figure 3.8, embodies cross frames and

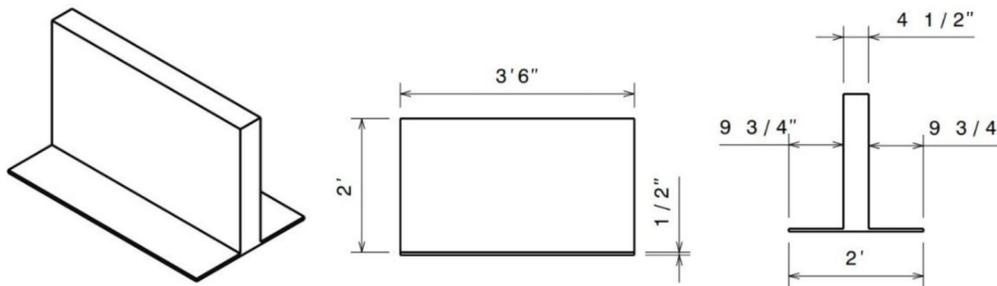


Figure 3.3 Isometric, front, and side views of Component 1.

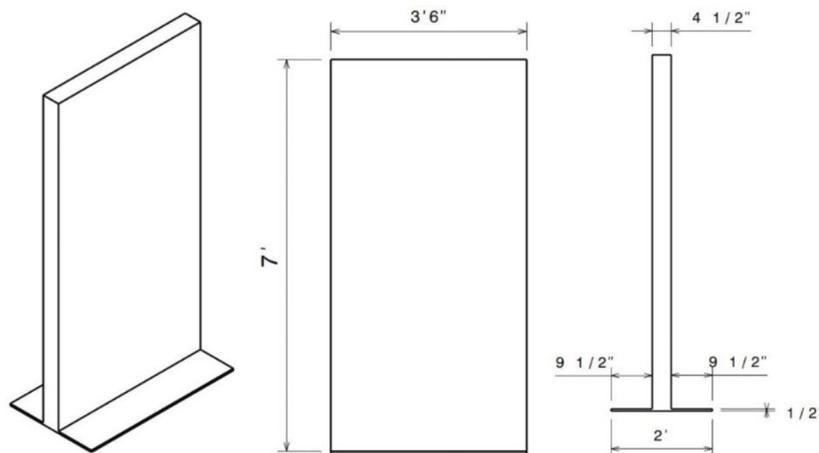


Figure 3.4 Isometric, front, and side views of Component 2.

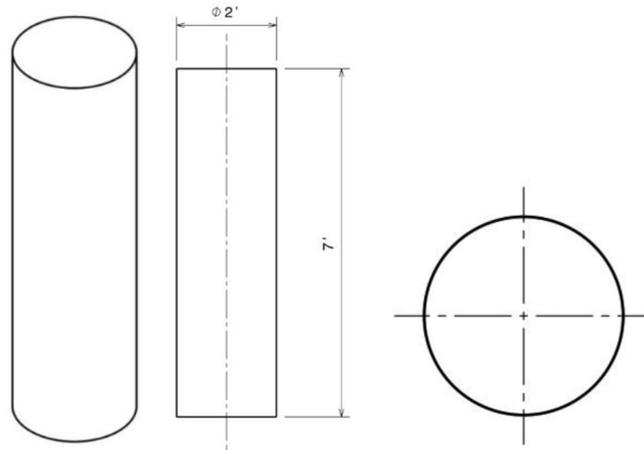


Figure 3.5 Isometric, front, and top views of Component 3.

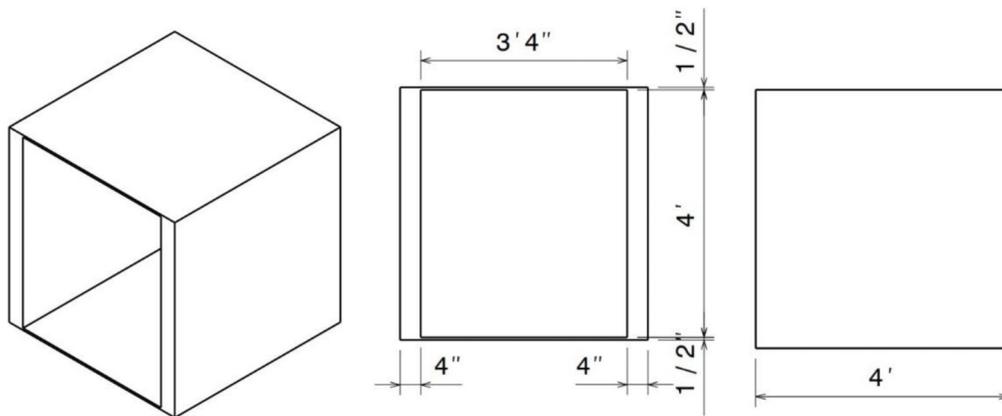


Figure 3.6 Isometric, front, and side views of Component 4.

bracing elements typical of bridge structures. It challenges the UAS's ability to navigate through and within slender, elongated structures such as K frames and truss elements. Its dimensions are an internal width of 4 feet 4 inches, an external width of 5 feet, a height of 6 feet, and a depth of 4 feet. Additionally, it features gusset plates with varying dimensions, the base measures 12 inches (square), while the top and bottom lengths are 12 inches. The middle length spans 16 inches, and the gusset plate's height is 18 inches.

3.5.1.6 Component 6. Component 6, as depicted in Figure 3.9, represents box structures and emulates tight spaces commonly found beneath bridge structures with vertical surfaces. It is designed to assess the UAS' capability to inspect from a bottom-up perspective, challenging it to observe both the ground and ceiling simultaneously. The dimensions for this component include an internal width of 3 feet 4 inches, an external width of 4 feet, a height of 7 feet, and a depth of 4 feet.

3.5.1.7 Component 7. Component 7, depicted in Figure 3.10, simulates environments where direct line-of-sight is severely restricted. This component represents scenarios where the pilot lacks visual access from the ground and must inspect confined and rounded spaces, increasing navigation challenges. Such spaces can be commonly found in abutments, piers, and decks. The dimensions for this component include an internal width of 5 feet 6 inches, an external width of 6 feet 2 inches, a height of 4 feet, and a depth of 5 feet 6 inches. The circular element within has a diameter of 2 feet and a height of 4 feet, which can be adjusted to align with the overall component's height.

3.5.2 Elements Inside the Evaluation Chamber

3.5.2.1 Element S1. Element S1, depicted in Figure 3.11, is a steel wide-flange beam featuring longitudinal stiffeners. This element emulates inspection areas between floor beams in confined spaces and focuses on welds and concealed beam cracks. The primary defects associated with this element are cracks and corrosion.

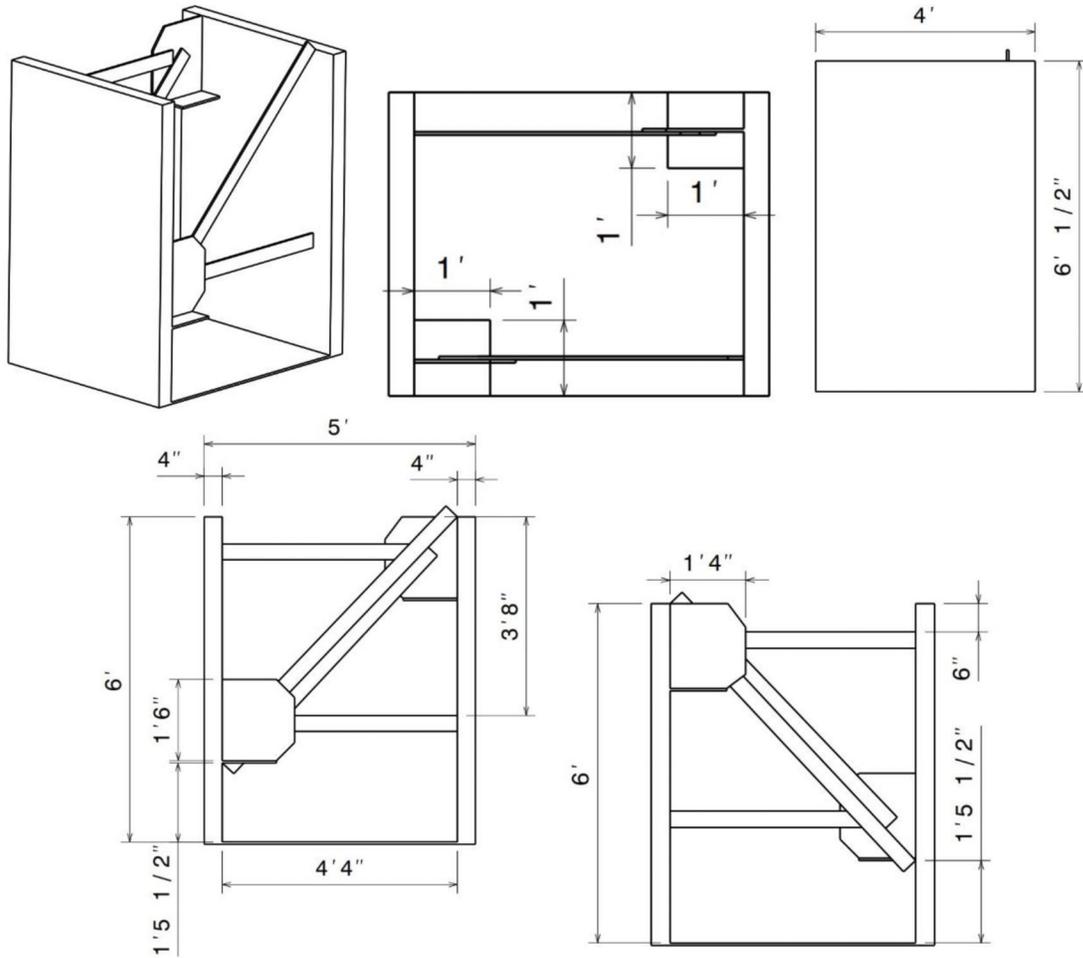


Figure 3.7 Isometric view, top view, side view, front view, and back view of Component 5.

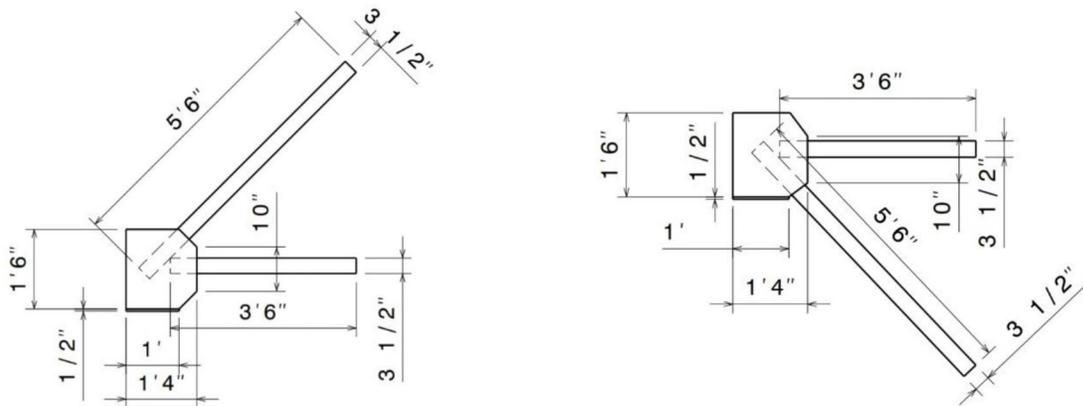


Figure 3.8 Part details of Component 5.

3.5.2.2 Element S2. Element S2, as illustrated in Figure 3.12, is a steel beam with longitudinal and transversal stiffeners. This design facilitates inspections of the web's longitudinal areas, the flanges, and the stiffeners. Notably, one side of the web challenges the UAV's camera with overexposed conditions. The

primary defects this element focuses on are corrosion and deformations due to impact.

3.5.2.3 Element S3. Element S3, depicted in Figure 3.13, is a steel beam with a missing flange and a section of the web. Its elevated position facilitates the

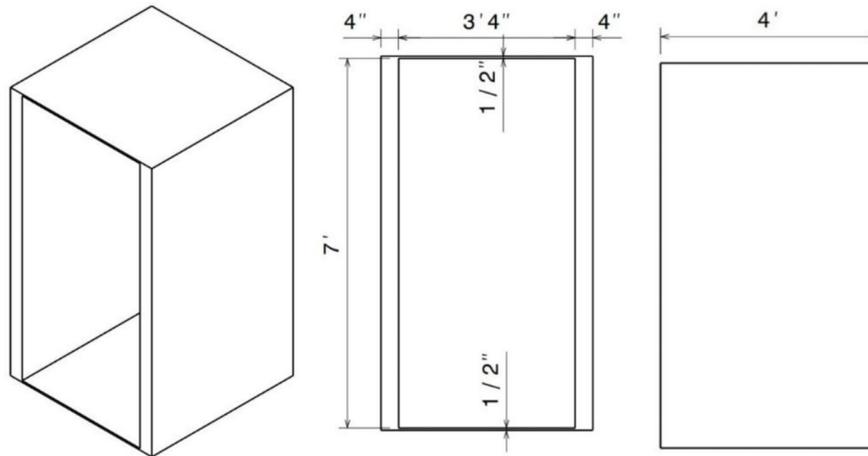


Figure 3.9 Isometric view, front view, and side view of Component 6.

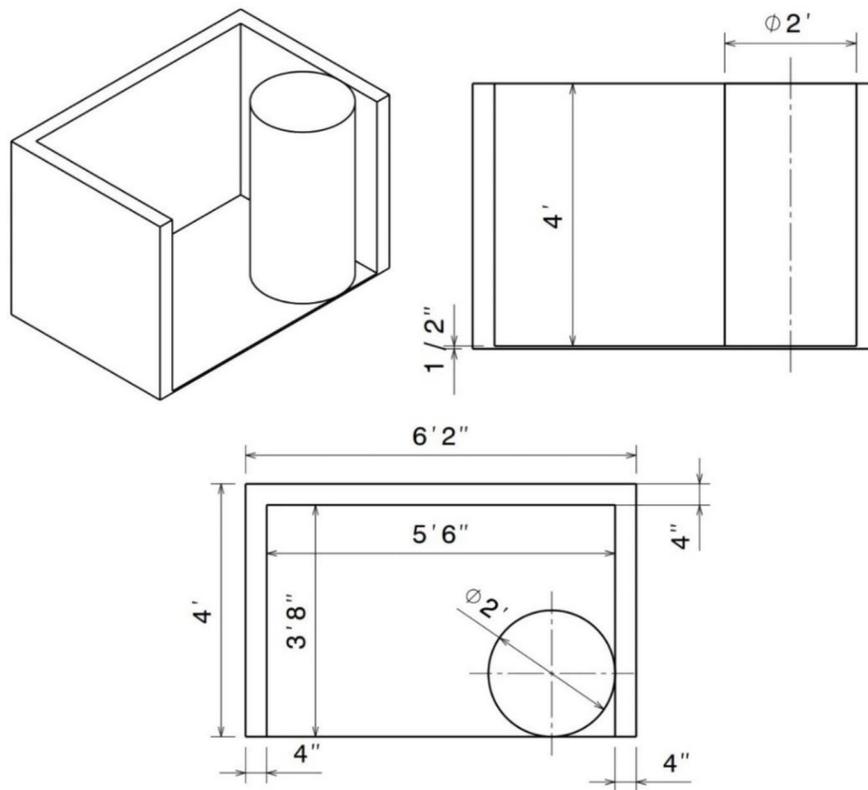


Figure 3.10 Isometric view, front view, and top view of Component 7.

inspection of elements distant from the ground. Additionally, one side of the web subjects the UAV's camera to overexposed conditions. This element primarily examines defects such as corrosion, cracks, and deformations resulting from impact.

3.5.2.4 Element S4. Element S4, as shown in Figure 3.14, is a steel beam with longitudinal and transversal stiffeners. This element focuses on identifying defects like cracks and corrosion.

3.5.2.5 Element S5. Element S5, depicted in Figure 3.15, is a steel plate featuring four holes. It is positioned to investigate ground effects for small components. The primary defects examined within this element are corrosion and cracks.

3.5.2.6 Element S6. Element S6, shown in Figure 3.16, is a small steel beam painted on the side visible to the UAS. Its positioning enables the exploration of ground effects for compact components, especially those

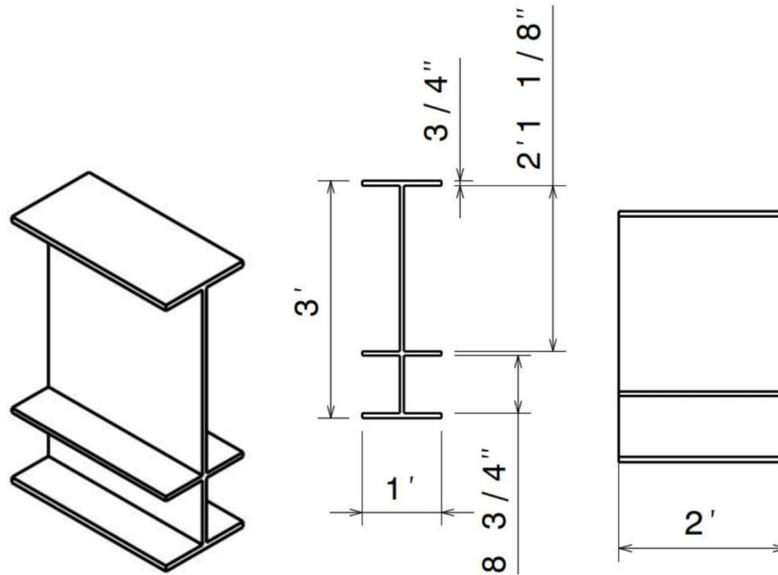


Figure 3.11 Isometric view, side view, and front view of element S1.

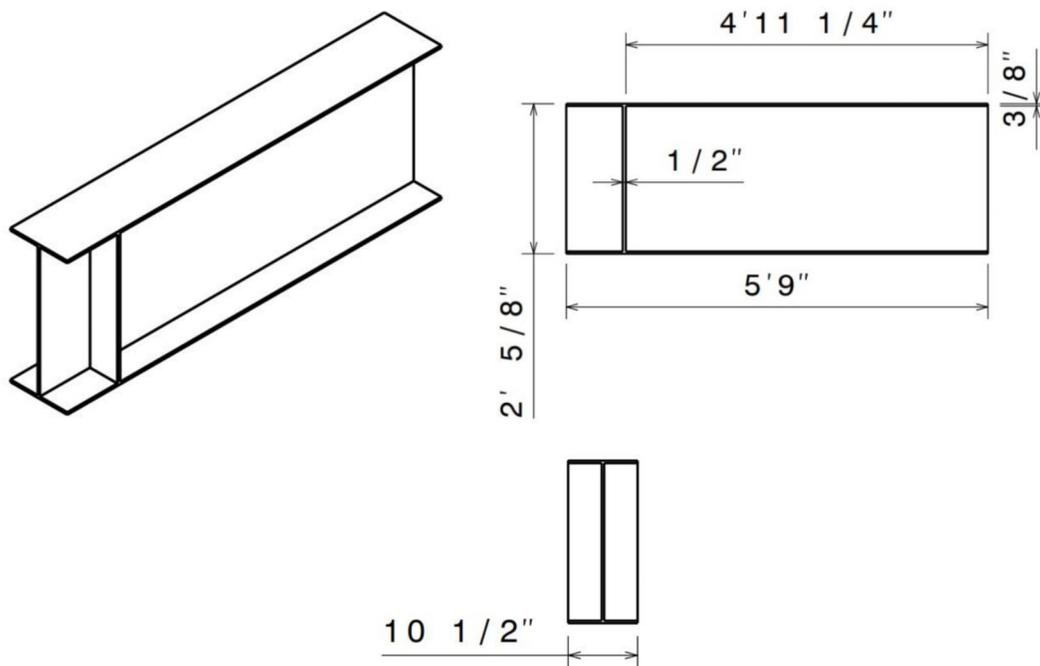


Figure 3.12 Isometric view, front view, and side view of element S2.

challenging to access due to adjacent structures. The primary defect examined within this element is corrosion.

3.5.2.7 Element S7. Element S7, depicted in Figure 3.17, is a steel element with bolts on its sides and rivets on the bottom plate facing upwards. Its placement mirrors conditions where adjacent sections hinder easy access to inspect bolts and rivets. The defects identified within this element focus on corrosion and cracks found in the rivets and bolts.

3.5.2.8 Element S8. Element S8, illustrated in Figure 3.18, consists of two intersecting steel plates featuring shear studs on the floor directed upwards. These shear studs are included to capture details previously missed in other components. Its positioning is indicative of sites where adjacent sections can obstruct easy access. The element focuses on identifying defects like corrosion and issues with the shear studs, with at least one of these studs displaying deformations.

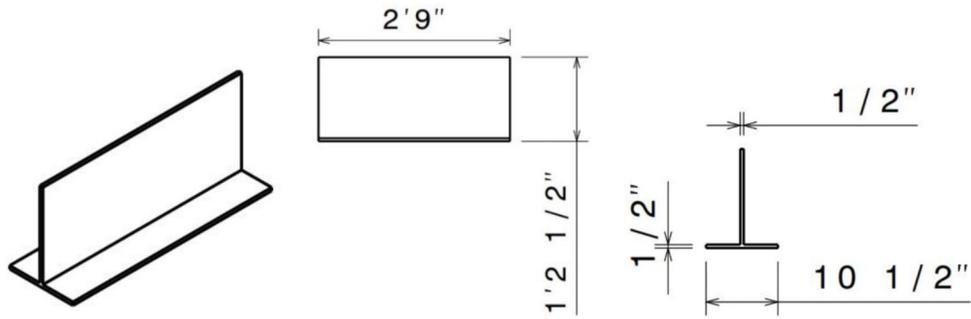


Figure 3.13 Isometric view, front view, and side view of element S3.

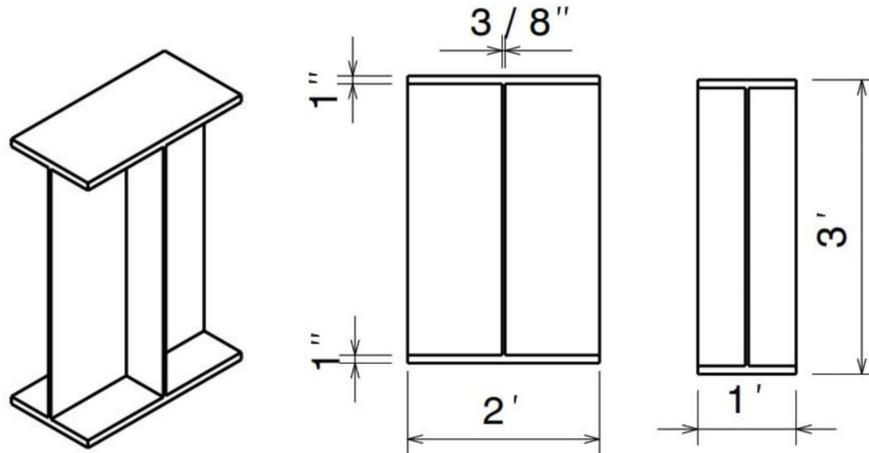


Figure 3.14 Isometric view, front view, and side view of element S4.

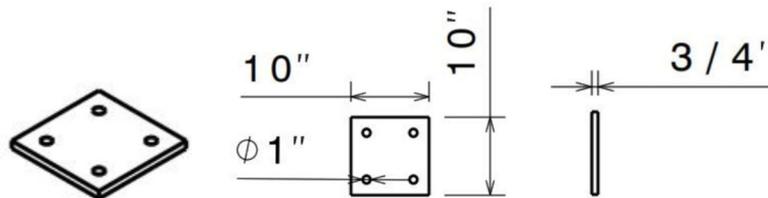


Figure 3.15 Isometric view, top view, and side view of element S5.

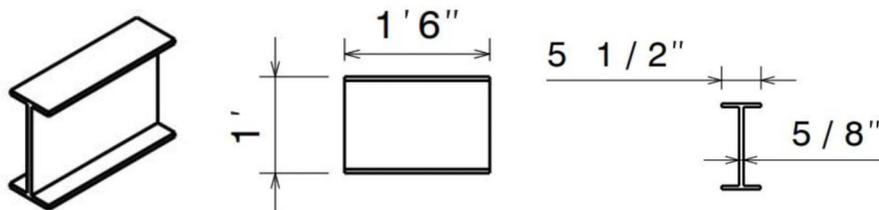


Figure 3.16 Isometric view, front view, and side view of element S6.

3.5.2.9 Element S9. Element S9, depicted in Figure 3.19, is a pin and hanger system split into two sections. While the division is not obligatory, it offers additional areas with restricted access. This element primarily focuses on identifying corrosion-related defects, including those in the pin and hanger connections, the base metal, and accumulation in the connection itself.

3.5.2.10 Element S10. Element S10, illustrated in Figure 3.20, features a steel section with a corrugated pattern that displays varying degrees of corrosion and section loss, significantly altering its original shape. The placement of this element allows for a comprehensive inspection, covering at least 270° around the structure. The primary defects to identify in this component are heavy corrosion and section loss.

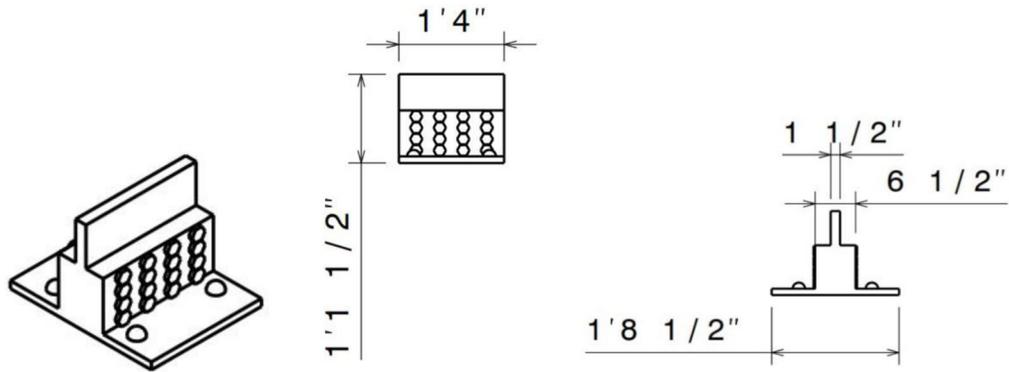


Figure 3.17 Isometric view, front view, and side view of element S7.

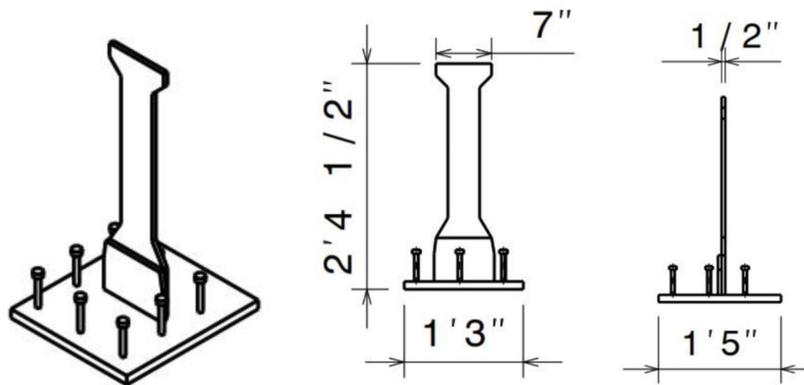


Figure 3.18 Isometric view, front view, and side view of element S8.

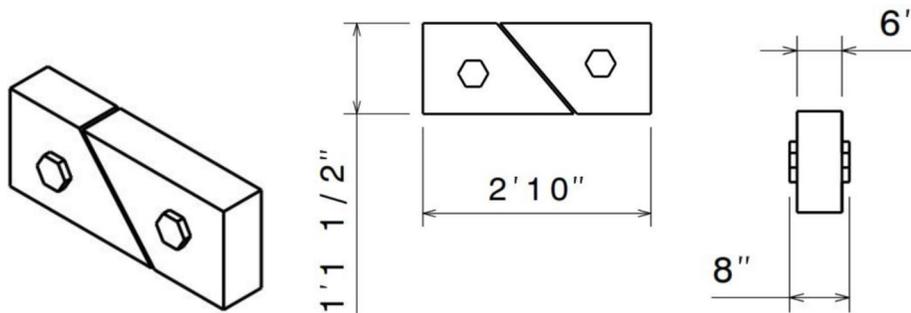


Figure 3.19 Isometric view, front view, and side view of element S9.

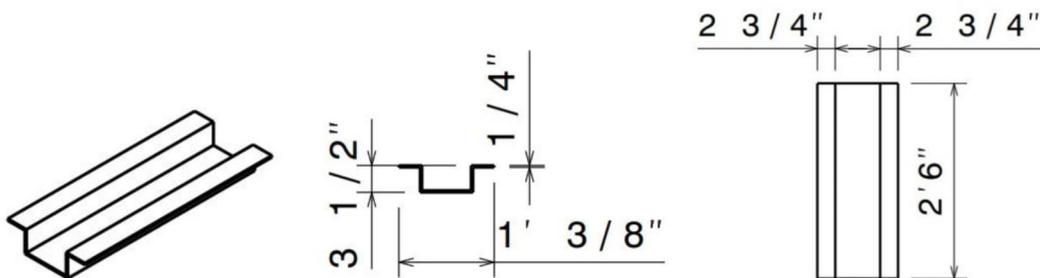


Figure 3.20 Isometric view, front view, and top view of element S10.

3.5.2.11 **Element S11.** Element S11, as depicted in Figure 3.21, is a steel structure with a corrugated pattern. It showcases a variety of corrosion levels and

section losses, drastically deviating from its original form. Its position emphasizes the ground effect and restricts the visual inspection range. The primary

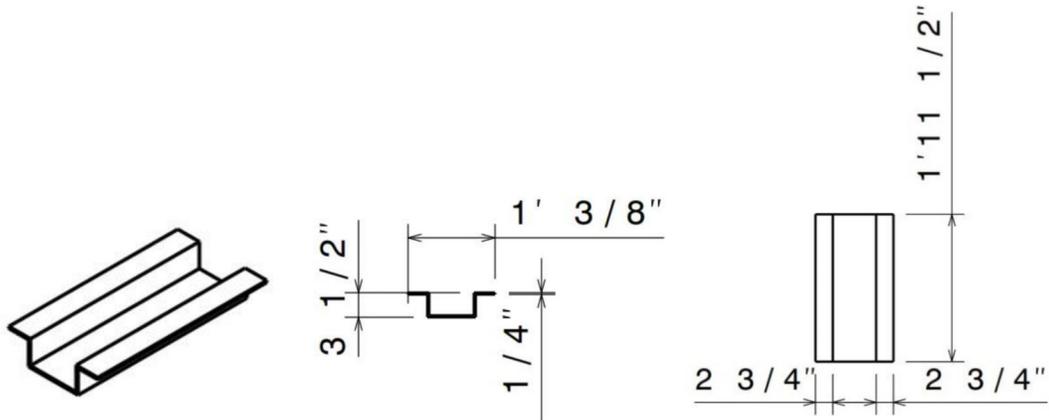


Figure 3.21 Isometric view, front view, and top view of element S11.

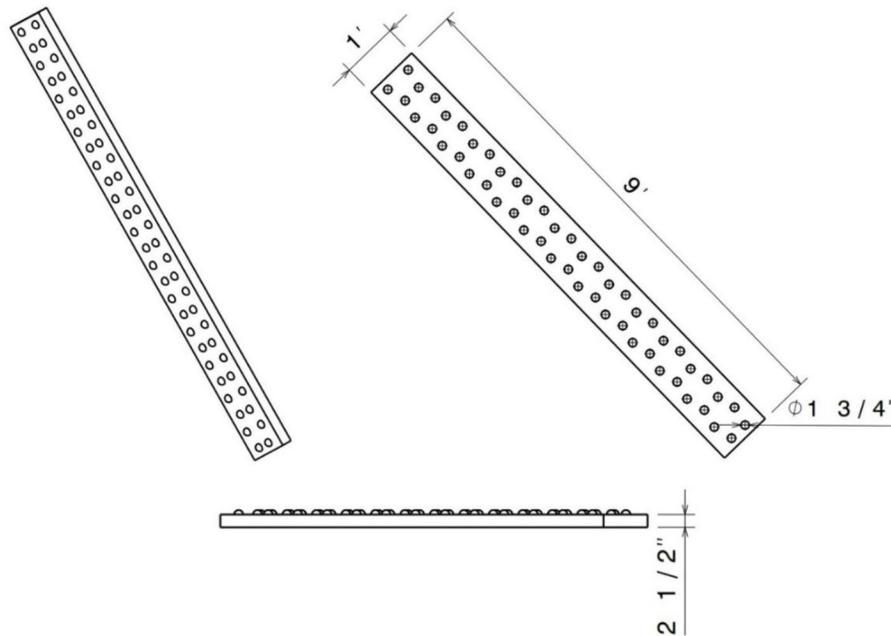


Figure 3.22 Isometric view, front view, and side view of element S12.

defects associated with this component are heavy corrosion and section loss.

3.5.2.12 Element S12. Element S12, illustrated in Figure 3.22, is a steel plate featuring 50 rivets aligned longitudinally. While some rivets display cracks and defects, others remain intact. The primary defects associated with this component are corrosion and cracks found along the rivets.

3.5.2.13 Element S13. Element S13, depicted in Figure 3.23, is a thick steel plate with holes aligned longitudinally. Its placement simulates locations with challenging access due to surrounding sections, yet its front face remains evident to the observer. The primary defects associated with this component are cracks surrounding the holes and corrosion.

3.5.2.14 Element S14. Element S14, illustrated in Figure 3.24, is a steel hanger complemented with a base. Its size offers flexibility for placement within the evaluation chamber. However, it should be positioned where nearby elements obstruct easy access to all its surfaces. The primary defects to look out for in this component are corrosion and cracks.

3.5.2.15 Element S15. Element S15, depicted in Figure 3.25, is a tee or WT beam positioned in a location that restricts access to one of its sides. Potential defects in this component to be mindful of are corrosion and, if applicable, cracks.

3.5.2.16 Element C1. Element C1, illustrated in Figure 3.26, consists of two interconnected reinforced concrete L-shaped blocks. At their juncture, a shear

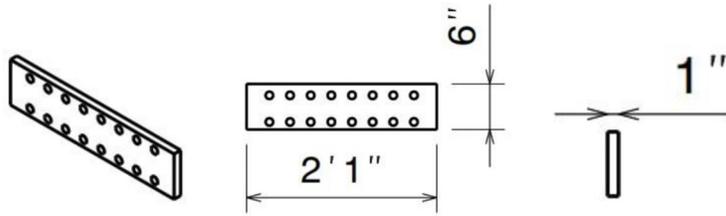


Figure 3.23 Isometric view, front view, and side view of element S13.

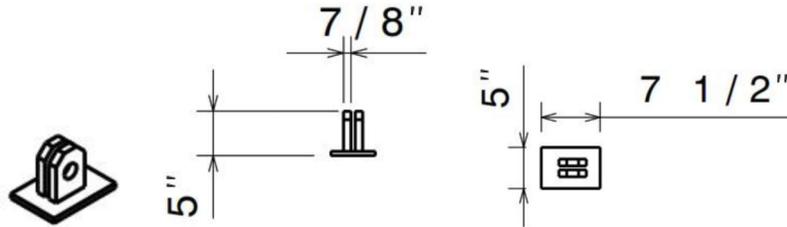


Figure 3.24 Isometric view, side view, and top view of element S14.

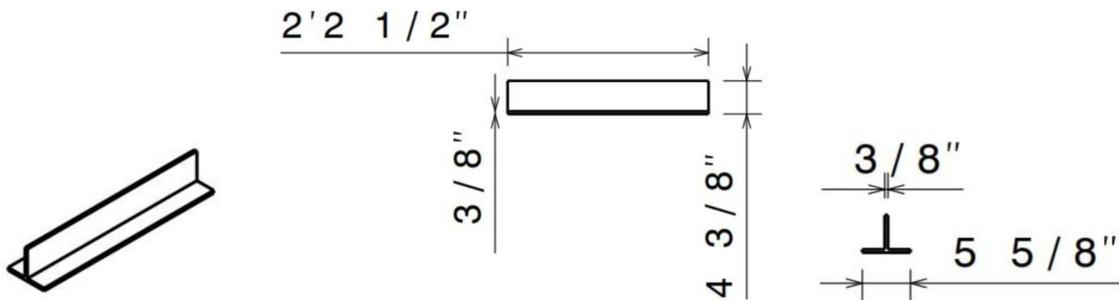


Figure 3.25 Isometric view, front view, and side view of element S15.

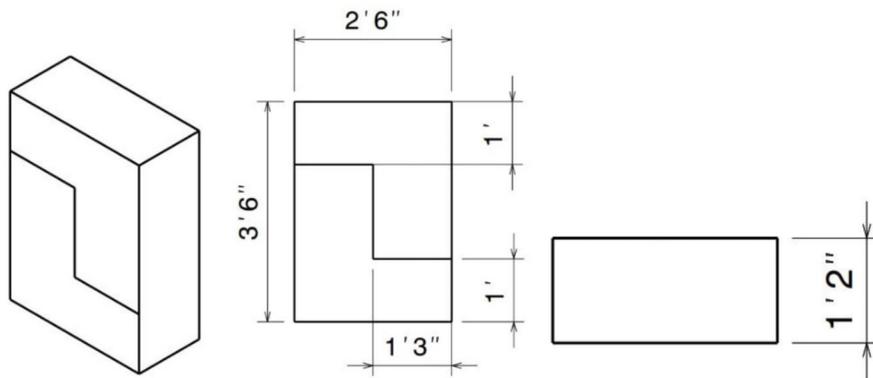


Figure 3.26 Isometric view, front view, and top view of element C1.

fracture is evident. Its placement limits accessibility to one side. This component can exhibit defects such as shear cracks in the reinforced concrete, exposed rebar, and spalling.

3.5.3 Images and Resolution Charts

3.5.3.1 Resolution chart. Resolution charts are a standard test of the ability of an optical system, e.g.,

cameras, to produce detailed images. When capturing pictures in outdoor environments, the picture can distort perspective, straight lines, or modify colors. These changes can hide or change how a defect is perceived, e.g., hide or miss cracks, ignore corrosion, or show significant portions of the element in a different color. Resolution charts have been used in the chamber to assess this behavior. The selected chart will contain elements of known length and width to compare with

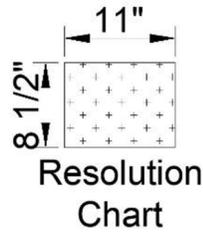


Figure 3.27 Resolution chart representation inside the evaluation chamber.

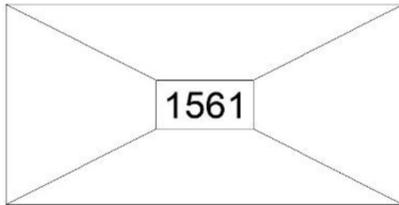


Figure 3.28 Illustration of an image with a 4-digit identifier.

the picture results. In addition, following the principles of color theory, the chart will also present primary (red, yellow, and blue), secondary (a 50/50 combination of any two primary colors), and tertiary colors (a 25/75 or 75/25 combination of a primary color and secondary color).

Three copies of the DGK Color Tools High-Resolution Chart (8.5 inches \times 11 inches) are positioned on specific components within the evaluation chamber. A hatched patterned rectangle, as shown in Figure 3.27, denotes a resolution chart. While the chart developer offers techniques for evaluating images containing a resolution chart, those methods are not used in this document.

3.5.3.2 Images. An additional appendix not presented in this report showcases high-quality images of defects in steel and concrete structures, accompanied by an in-depth description of each defect. The second digit from the left indicates the type of material depicted in the image: 5 for concrete and 7 for steel. An illustration of an image is presented in Figure 3.28. The appendix comprises 120 images showcasing defects in steel and concrete structures, including corrosion, cracks, spalling, delamination, staining in concrete, weld defects, and more.

Images within the appendix can be swapped with others of the same material type. For instance, a concrete image (identified by the second digit as 5) can only be replaced with another concrete image, and the same principle applies to steel images.

3.5.4 Modified UAS Evaluation Chamber

Figure 3.29 depicts the evaluation chamber from an isometric view, highlighting the positions of various elements. Figure 3.30 and Figure 3.31 provide a more detailed labeling of these elements. The images related to specific dimensions and distances between elements

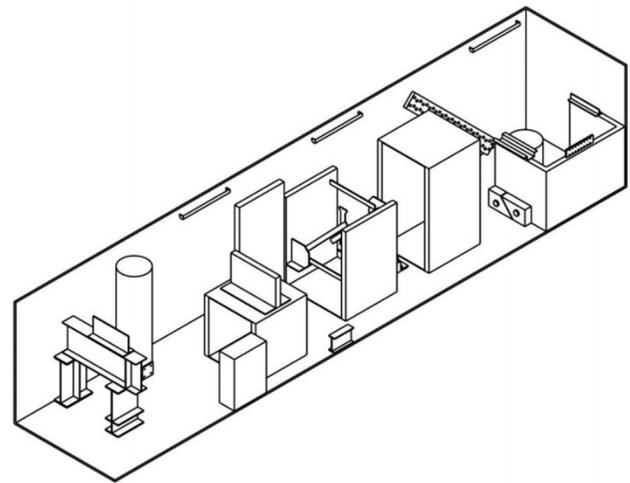


Figure 3.29 General isometric view of elements inside the evaluation chamber.

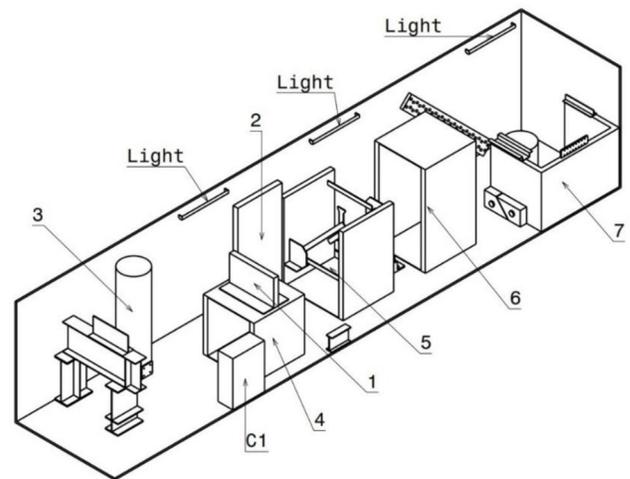


Figure 3.30 General isometric view with labels of components, concrete elements, and lights inside the evaluation chamber.

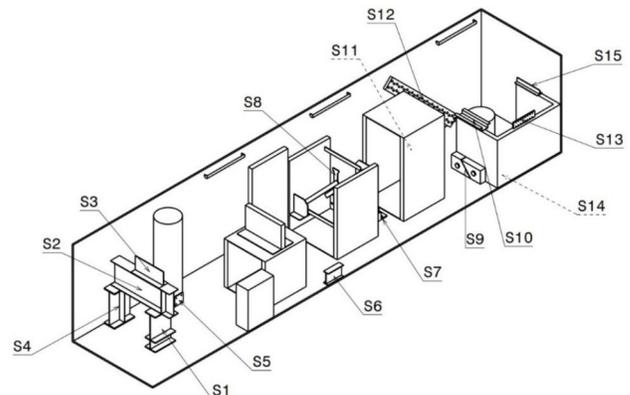


Figure 3.31 General isometric view of steel elements inside the evaluation chamber.

have been removed from this report to maintain confidentiality. They remain in the possession of the sponsor states for reference and future implementation.

3.5.5 Location of Images Inside the UAS Evaluation Chamber

Images of steel and concrete defects have been placed in multiple locations in the faces of components inside the evaluation chamber. The location was selected based on the common arrangement of structural elements in bridge structures. The image location per component is presented below, with dimensions to facilitate placement in each face. The face identifier corresponds to the components presented in Section 3.5.1. The face identifier starts with the letter “F” and is followed by the component and face numbers.

3.5.5.1 Component 1. Component 1 images are presented in Figure 3.32 and Figure 3.33.

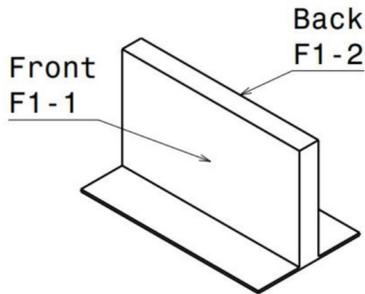


Figure 3.32 Faces of Component 1.

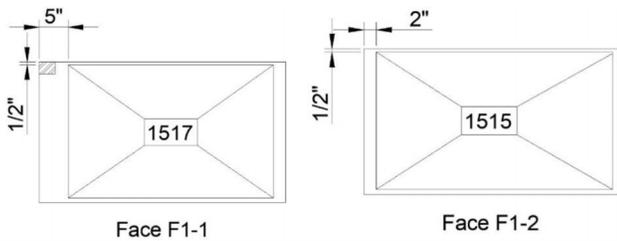


Figure 3.33 Images in Component 1.

3.5.5.2 Component 2. Component 2 images are presented in Figure 3.34 and Figure 3.35.

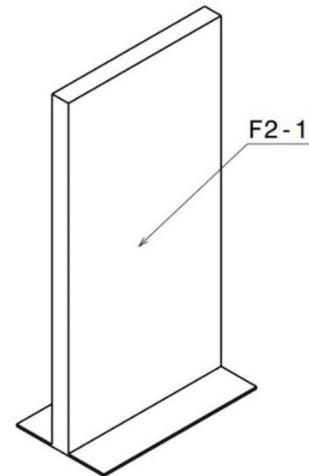


Figure 3.34 Faces of Component 2.

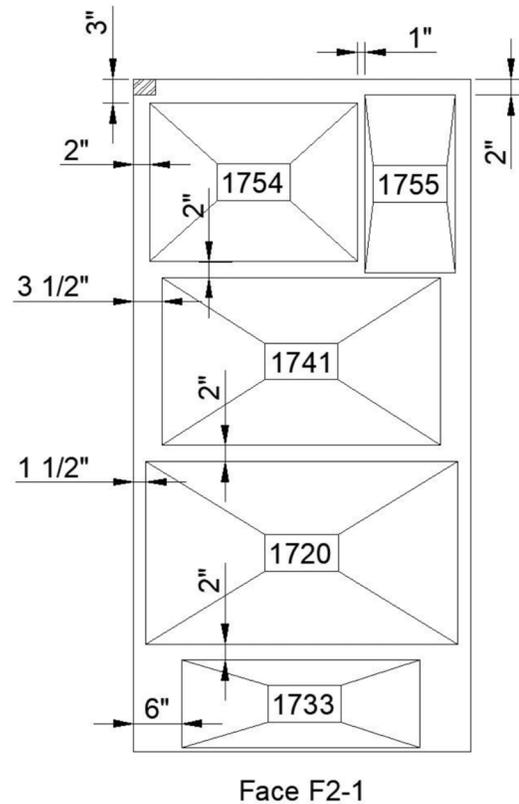


Figure 3.35 Images in Component 2.

3.5.5.3 Component 3. Component 3 images are presented in Figure 3.36 and Figure 3.37.

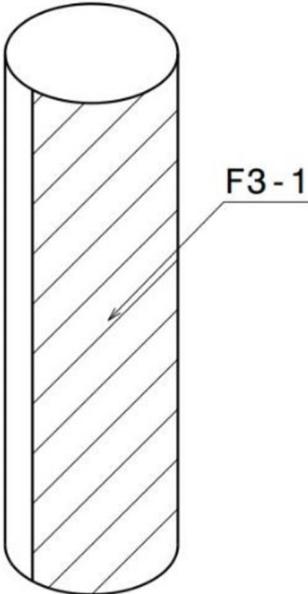
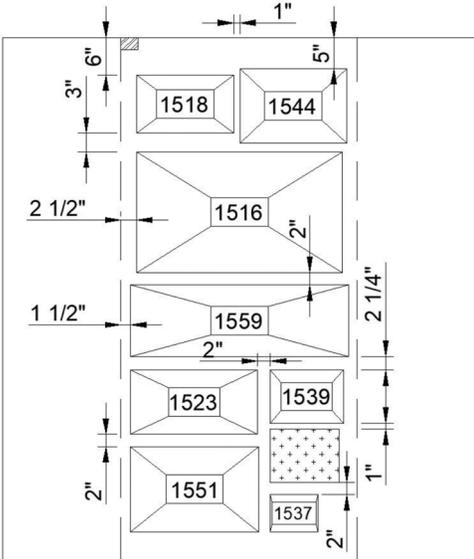


Figure 3.36 Faces of Component 3.



Face F3-1

Figure 3.37 Images in Component 3.

3.5.5.4 Component 4. Component 4 images are presented in Figure 3.38 and Figure 3.39.

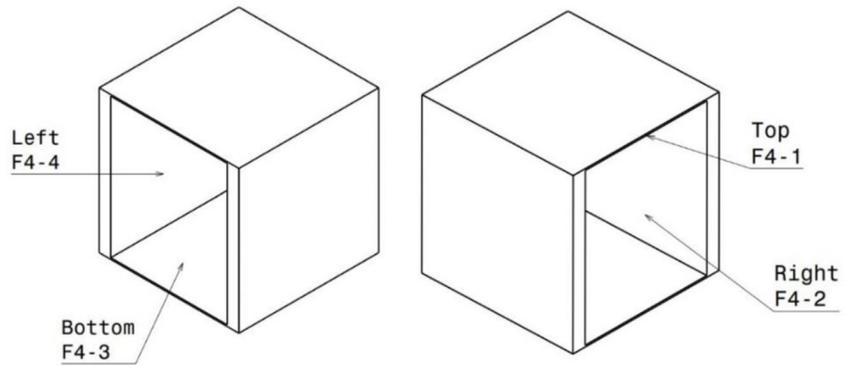


Figure 3.38 Faces of Component 4.

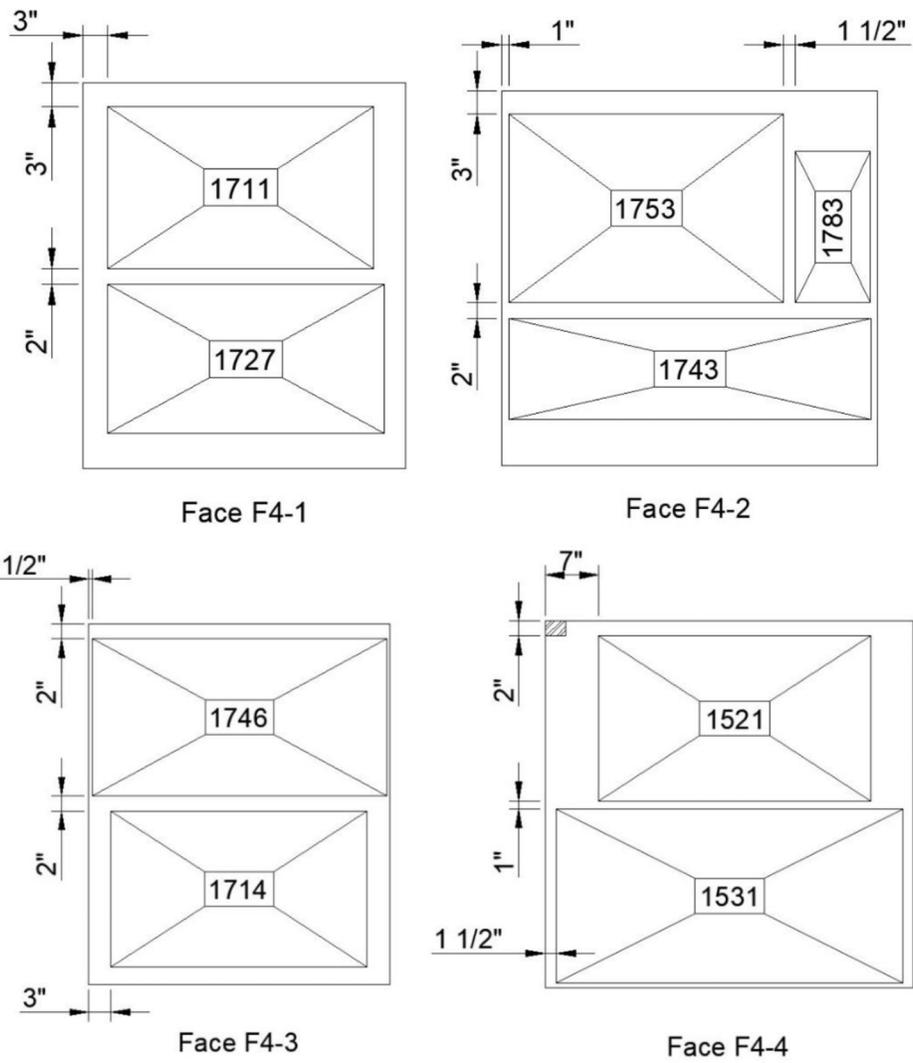


Figure 3.39 Images in Component 4.

3.5.5.5 Component 5. Component 5 images are presented in Figure 3.40 and Figure 3.41.

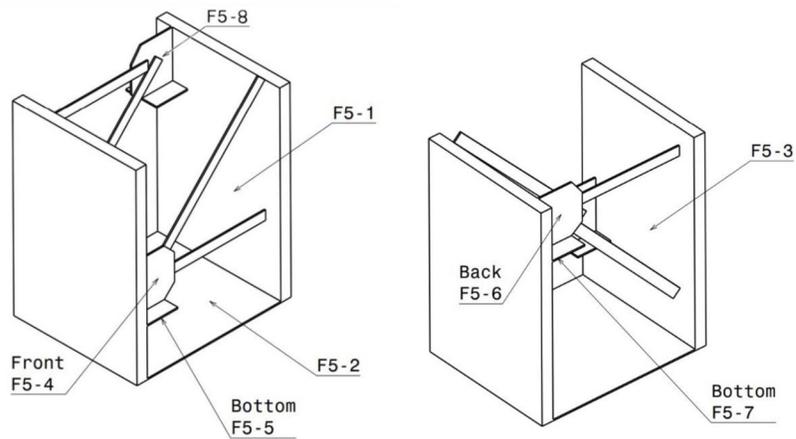


Figure 3.40 Faces of Component 5.

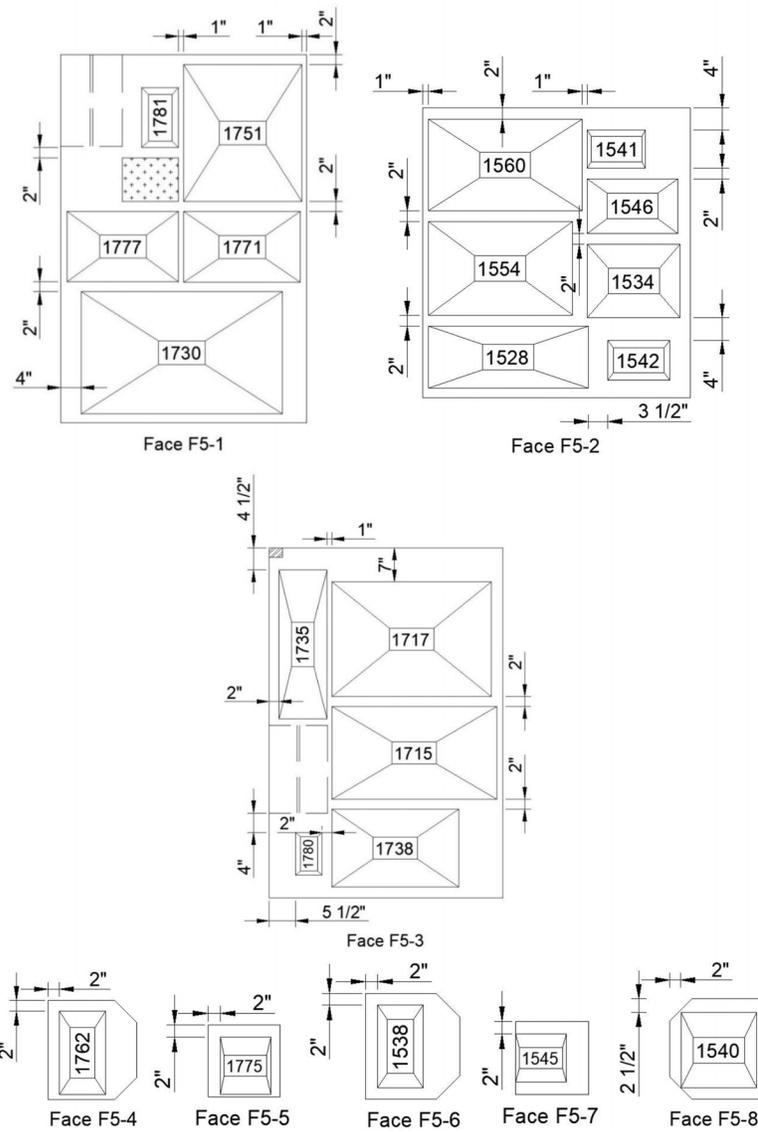


Figure 3.41 Images in Component 5.

3.5.5.6 Component 6. Component 6 images are presented in Figure 3.42 and Figure 3.43.

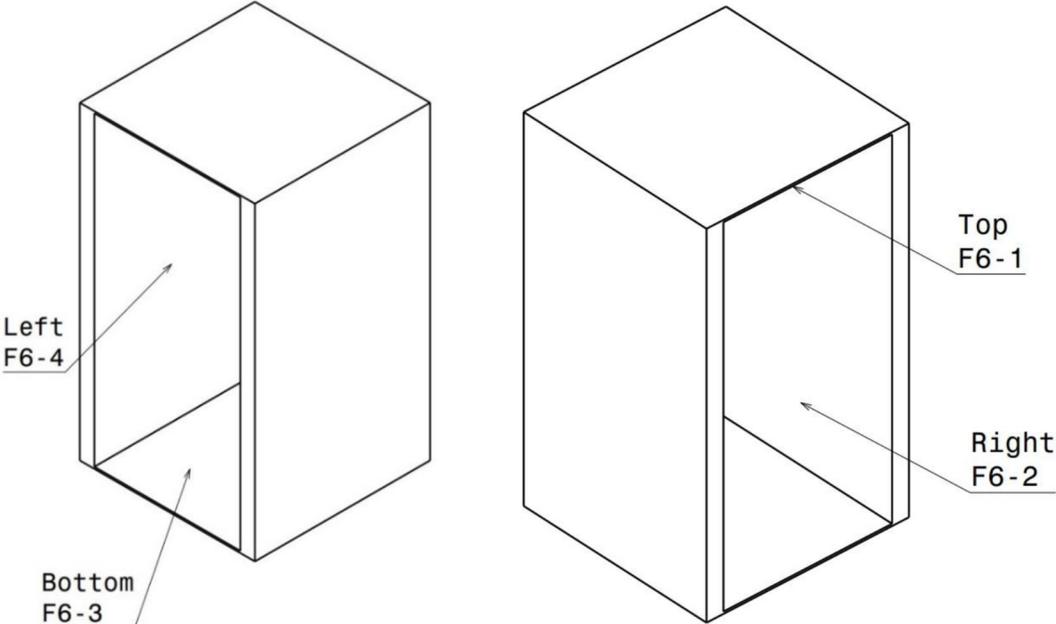


Figure 3.42 Faces of Component 6.

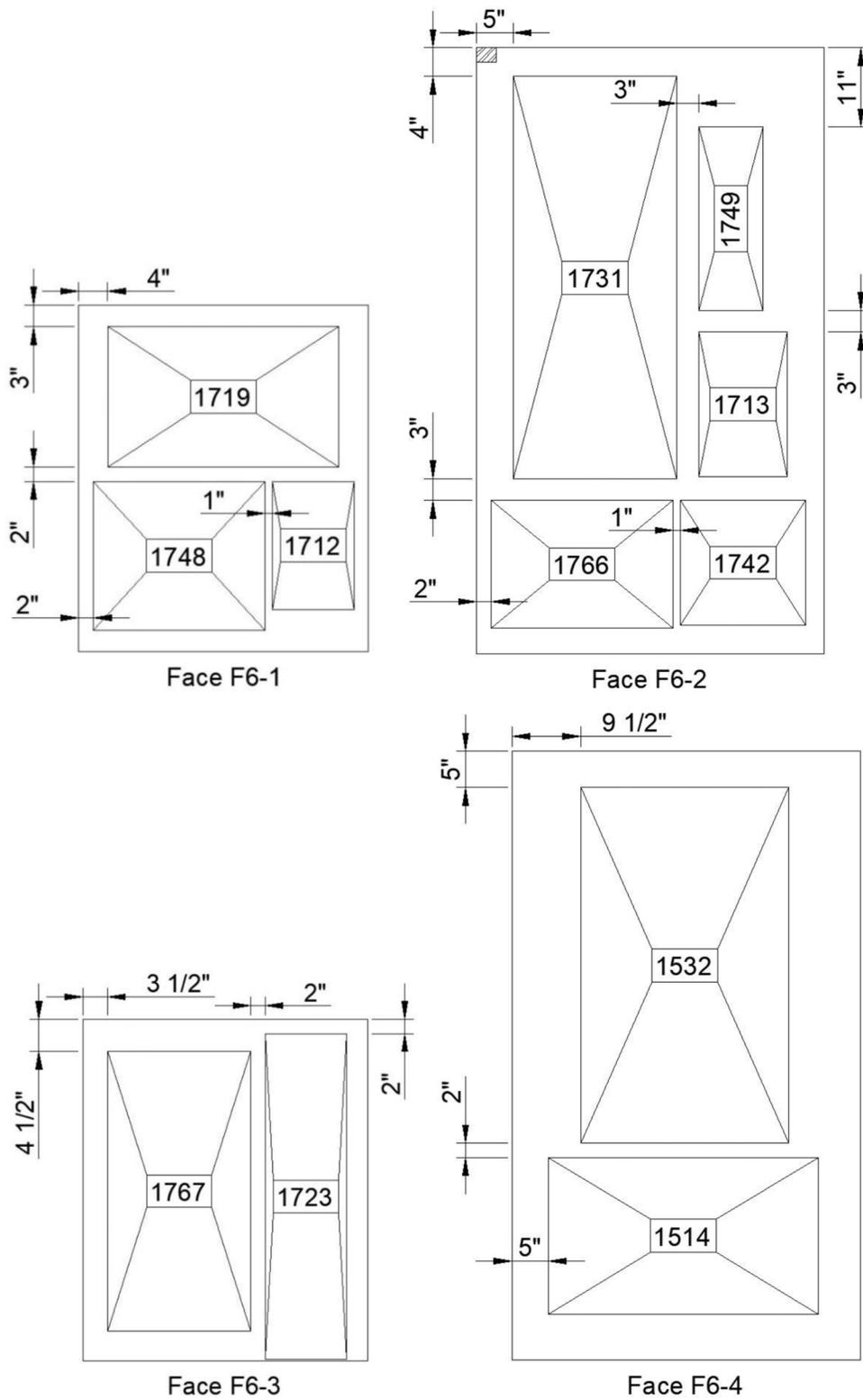


Figure 3.43 Images in Component 6.

3.5.5.7 Component 7. Component 7 images are presented in Figure 3.44 and Figure 3.45.

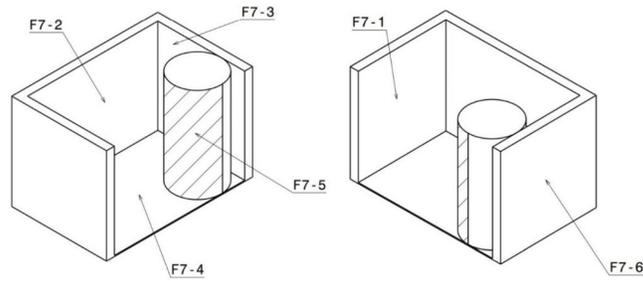


Figure 3.44 Faces of Component 7.

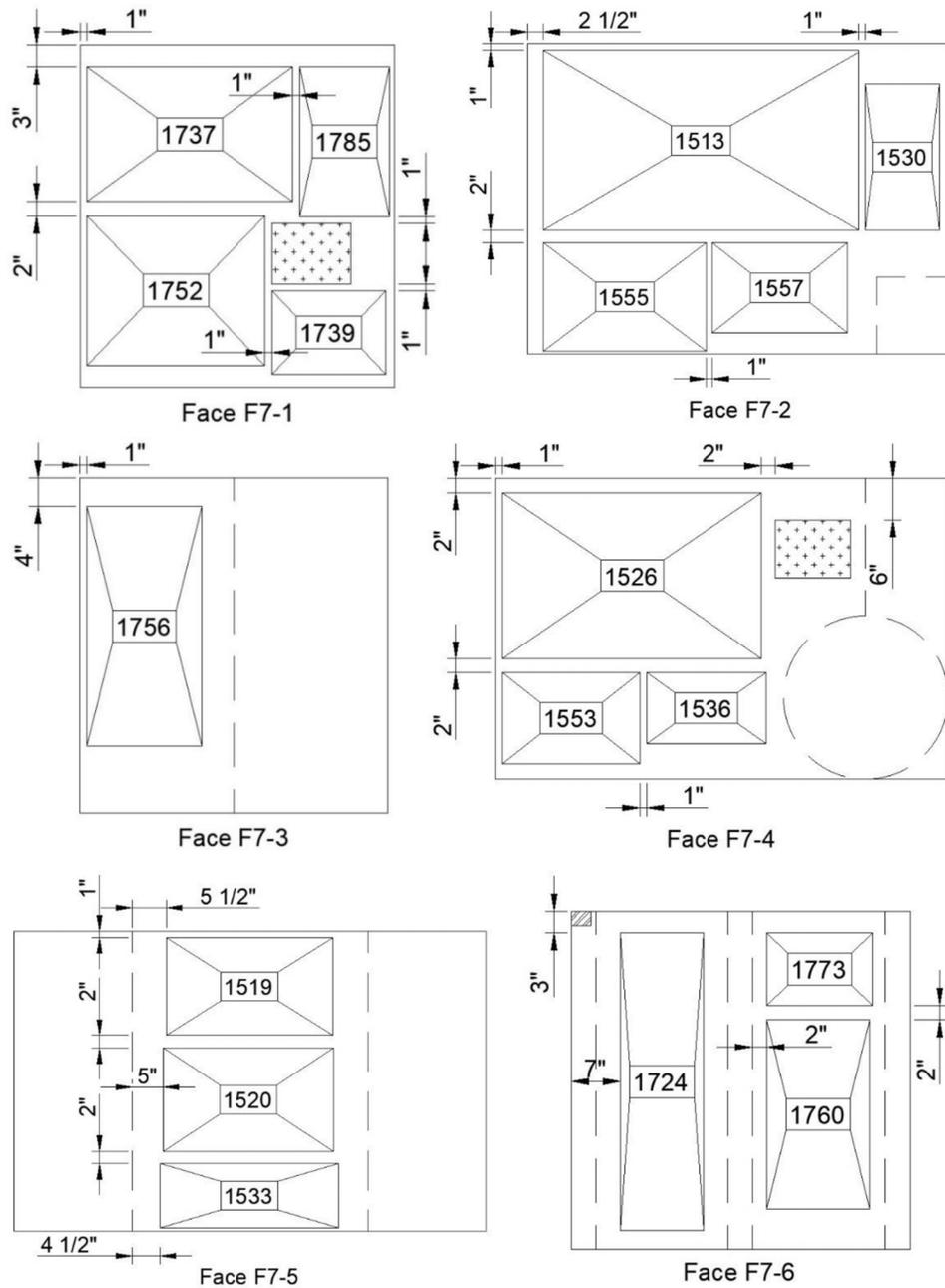


Figure 3.45 Images in Component 7.

3.6 Procedure for Testing

3.6.1 Before the Test

Before starting the test, the UAS must adhere to the preflight checklist in the standard's appendix. The UAS should be assessed for suitability in the evaluation chamber by ensuring it adheres to the weight and horizontal dimension limitations specified in Chapter 2. Moreover, the UAS should be capable of flying and maneuvering without a GPS signal.

A thorough airframe inspection is mandatory to ensure the UAS is maintained according to the manufacturer guidelines. All its components, including the motor, propellers, battery, transmitter, and additional payload, must be undamaged. All compartments must be sealed before takeoff.

Regarding batteries and data collection, the proctor must identify and record the number of batteries to be used, the unique label number, and the manufacturer's code. Any data acquisition tools, like a camera, should be appropriately set up, ensuring adequate storage space for information.

Once the proctor confirms the UAS's suitability for evaluation and observes no visible damage, the pilot will position the UAS at the container's entrance for takeoff. The pilot, visual observer, or the pilot in command must refrain from entering the evaluation chamber before, during, or after the test. In emergencies, the test proctor will retrieve the UAV from the chamber.

3.6.2 During the Test

Before taking off, the UAS must adhere to the flight checklist outlined in the standard's appendix. The designated area for takeoff is the entrance of the chamber. Pilots should maneuver the UAV from this point, though they can move outside the container and adopt any position necessary for successful test completion. The pilot is advised to maintain a distance of 2 to 5 feet from the container's entrance for effective navigation inside the evaluation chamber. Under no circumstances is the pilot permitted to enter the container. In emergencies within the chamber, the test proctor will execute the necessary procedures. The takeoff and landing times must be documented for each battery utilized during the test.

The UAS can navigate any part of the evaluation chamber to visually inspect and collect data on all steel, concrete, and other components. The test concludes once the UAS has obtained sufficient information to comprehensively assess the chamber's internal elements.

Landings are only permitted at the proctor-established takeoff point at the evaluation chamber's entrance. If the UAS needs a battery replacement during the test, it must ensure its return to the takeoff point from any location within the chamber. Takeoffs within the evaluation chamber are strictly forbidden except in emergencies.

3.6.3 After the Test

The test concludes once the inspector determines that the UAS has identified all potential defects within the evaluation chamber. This assessment can be based on real-time flight observations or through post-processing analysis.

4. DEVELOPMENT OF A STANDARD GRADING ASSESSMENT FOR THE UAS EVALUATION CHAMBER FOR BRIDGE INSPECTION

This testing methodology details the procedure for providing a final score and qualification to the report provided after completion of the UAS evaluation chamber test for bridge inspection. The standard grading criteria quantitatively assess the UAS performance inside the evaluation chamber.

4.1 Objective of the Performance-Based Assessment

The objectives of the standard grading assessment for the UAS evaluation chamber are as follows.

- Assess quantitatively the performance of small unmanned aerial systems (UAS) when collecting inspection data inside the UAS evaluation chamber.
- Develop qualitative assessment levels of expertise and their significance in field inspection environments.
- Provide a qualitative measure that relates the performance inside the UAS evaluation chamber with its performance in field environments.

4.2 Assessment Considerations

The standard grading assessment follows the evaluations and assessments considerations for training programs by the Federal Highway Administration (FHWA) National Highway Institute (NHI). The style and standards guide prescribes (NHI, 2022).

- The *assessment* may consist of objective methods, (...) the method might be presented in *performance-based formats*, such as skill demonstrations, case studies, or presentations.
- Assessment answer keys include a justification of the correct answer (...). Where necessary, it should include *tools to mitigate subjectivity in grading or scoring*. For (...) other performance-based formats, *create a rubric* that clearly details *assessment criteria, parameters, and levels*.
- When a performance-based outcome is assessed by *rubric*, make sure the learning outcome criteria include *specific, observable, and measurable descriptors* that define proficiency. It is acceptable to assign a numeric value to a proficiency level, but it is not necessary.
- The minimum passing score is *70 percent* (...).
- NHI recommends Bloom's Taxonomy of performance levels when writing learning outcomes.

Based on the previous considerations, the standard grading assessment for the UAS evaluation chamber

consists of an analytical scoring rubric and certification levels.

4.3 Analytical Scoring Rubric Considerations

The analytical scoring rubric assesses performance-based outcomes measured from the UAS performance in the evaluation chamber test. This grading tool is prepared to mitigate subjectivity in grading or scoring per the NHI considerations.

The analytical scoring rubric contains criteria, parameters, levels, and descriptors for each element inside the UAS evaluation chamber and the corresponding performance-based outcomes. According to NHI considerations, the descriptors are specific, observable, and measurable.

4.3.1 Performance-Based Outcomes

As described in Chapter 3, the UAS evaluation chamber assesses the UAS performance that mimics bridge inspection environments. In a real-life inspection, the bridge inspector is tasked with identifying and assessing findings in the structure inspected. These findings are known in the field as defects that can risk the structure's and its users' integrity. Therefore, the defects found in structural inspection drive the rubric's design and become the core of this assessment. The defects existing in the UAS evaluation chamber and identified for assessment using the analytic rubric have been obtained from the *AASHTO Manual for Bridge Element Inspection* (AASHTO, 2019). The performance-based outcomes have been developed using Bloom's Taxonomy, per NHI's recommendation, and divided into qualitative and quantitative.

4.3.1.1 Qualitative performance-based outcomes. The qualitative performance-based outcomes focus on identifying, describing, differentiating, and assessing defects in the UAS evaluation chamber and reporting any relevant defects. The inspection assessment contains any defect deemed relevant to be reported by the UAS for all the elements and components inside the UAS evaluation chamber. The report contains two types of assessments: a written description of the assessment and an element-level condition assessment according to the *AASHTO Manual for Bridge Element Inspection*. Qualitative assessments are required for all elements inside the chamber. The qualitative performance-based outcomes are the following.

Identify, describe, assess, and report any defect deemed relevant for concrete members related to the following items.

- delamination/spall/patched area,
- exposed rebar,
- efflorescence/rust staining
- cracking,
- abrasion/wear, and
- damage.

Identify, describe, assess, and report any defect deemed relevant for steel members related to the following.

- corrosion,
- cracking,
- connection,
- distortion, and
- damage.

4.3.1.2 Quantitative performance-based outcomes. The quantitative performance-based outcomes focus on identifying, describing, differentiating, and assessing defects in the UAS evaluation chamber and reporting any relevant defects. The report contains any defect deemed relevant to be reported by the UAS for all the elements and components inside the UAS evaluation chamber. The report contains a quantitative analysis of defects following the guidelines provided in the performance-based outcome and description from Table 4.1 and Table 4.2. Quantitative assessments are required for elements included in certain areas inside the chamber. This area is described in Section 4.7.

4.4 Certification Level Considerations

The UAS evaluation chamber has been divided into three areas that vary in accordance with the following considerations:

- the proximity of the elements to the entrance,
- location of component faces that are difficult to view or access,
- complex geometries,
- elements access with respect to other elements inside the chamber,
- operations beyond the visual line of sight, and
- skills required for bridge inspection.

The evaluation chamber is divided into three areas according to the three certification levels. The certification levels that a UAS can attain after completing the evaluation chamber are Level A, Level AA, and Level AAA. In Figure 4.1, the entrance is located on the right side of the image, and the yellow color ■ represents Level A, the mint green color ■ represents Level AA, and the lime green color ■ represents Level AAA (some measurements have been included in the figure to provide some scale to the reader).

All levels require qualitative assessment, but only levels AA and AAA require quantitative assessment.

4.5 Evaluation Chamber Components and Elements Grading Considerations

The UAS evaluation chamber contains components and elements for the performance-based assessment of UAS used in inspection. The evaluation chamber arrangement contains fifteen steel elements, one concrete element, and seven components. Further details and geometric considerations can be found in Section 3.5.

TABLE 4.1
Quantitative performance-based outcomes for concrete members

Concrete Members	
Defects	Quantitative Performance-Based Outcomes
Delamination/Spall/Patched Area	Determine the <i>diameter in inches</i> of a circle around a defect (delamination/spall/patched area), with the <i>center</i> located at the approximate center of the defect's area and the <i>circumference</i> passing by the farthest point from the center of the defect. If there are multiple nearby defects, provide separate diameters. If small and scattered, provide a <i>percentage as an integer</i> approximating the area of the element covered with delamination/spall/patched area.
Exposed Rebar	Determine the <i>number of steel bars</i> exposed in the element as an <i>integer</i> . Any level of exposure shall be taken into consideration for the number provided. Where the rebar is exposed, provide the <i>length of exposure in inches</i> .
Efflorescence/Rust Staining	Determine a <i>percentage as an integer</i> approximating the area of the element covered with efflorescence/rust staining. When approximating the percentage, the total area to compare shall be taken as the visible area.
Cracking (RC)	Determine the <i>crack width</i> of the widest crack and the least wide crack in the element <i>rounded to 1 decimal place in inches</i> . The measure to provide shall be the actual crack width, not the spalled or "eroded" surface that sometimes occurs adjacent to a crack. In addition, if two or more cracks are present, provide the <i>length of the shorter spacing</i> between cracks as an <i>integer</i> number in <i>inches</i> . Attach a picture of the identified cracks. For example, if there are 5 cracks spaced at various distances, give the distance between the two most closely spaced cracks.
Abrasion/Wear (PSC/RC)	Determine a <i>percentage in integer numbers</i> approximating the area of the element covered with abrasion/wear. When approximating the percentage, the total area to compare shall be taken as what is visible on that surface.
Damage	Provide a qualitative description of the damage. No quantitative performance-based outcome is required.

TABLE 4.2
Quantitative performance-based outcomes for steel members

Steel Defects	
Defects	Quantitative Description
Corrosion	Determine the <i>approximate surface area</i> of the element covered with corrosion as an <i>integer</i> . When approximating the percentage, the total area to compare shall be taken as the visible surface. The description shall be provided for individual parts of the element. If crevice (pack rust) corrosion is present, measure the <i>thickness</i> of the pack-out layer (where the maximum distortion is located) in the deepest area of the pack rust rounded to <i>2 decimal places</i> . Also, provide an estimate of the section loss at the free edges of the component where the pack-out is observed. If section loss is evident on the surface of a component, provide the <i>amount of section loss as a percentage</i> rounded to an integer. Steps of 10% in thickness loss shall be provided. For example, there is a 10% section loss on 15% of the surface, a 30% section loss on 5% of the surface, and a 0% section loss on 80% of the surface.
Cracking	Determine the <i>crack width</i> of the widest crack and the least wide crack in the element rounded to <i>2 decimal places in inches</i> . Attach a picture of the identified cracks.
Connection	Determine an <i>integer number</i> denoting the number of connection elements with defects, either requiring structural review or not. Provide an integer number for each type of connection along with its type. If a connection is formed by smaller elements with multiple defects (rivets, bolts, etc.), they shall be individually counted.
Distortion	Provide a qualitative description of the distortion. No quantitative description is required.
Damage	Provide a qualitative description of the damage. No quantitative performance-based outcome is required.

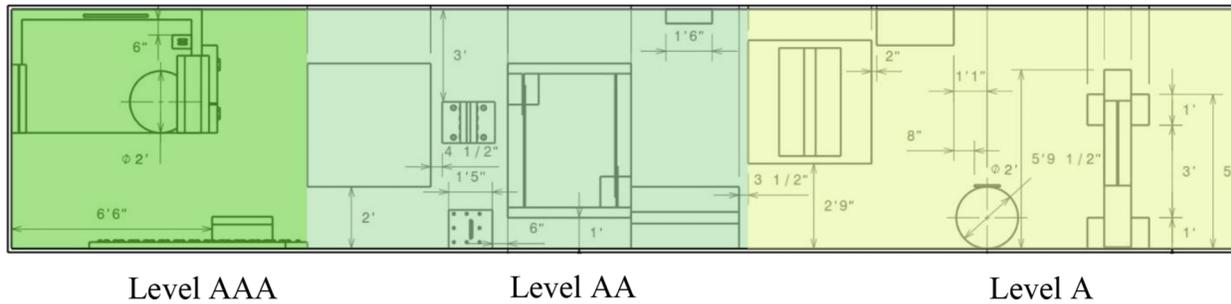


Figure 4.1 Certification levels for the UAS evaluation chamber. From right to left: Level A, Level AA, and Level AAA.

TABLE 4.3
Scoring guide per element and component

Level A Elements	Max Points	Level AA Elements	Max Points	Level AAA Elements	Max Points
S1	9	Component 2	15	S9	9
S2	9	S6	9	S10	9
S3	9	Component 5	69	S11	9
S4	9	S7	9	S12	9
S5	6	S8	9	S13	9
Component 3	27	Component 6	36	S14	9
C1	9	–	–	S15	9
Component 1	6	–	–	Component 7	60
Component 4	27	–	–	–	–
<i>Total</i>	<i>111</i>	<i>Total</i>	<i>147</i>	<i>Total</i>	<i>123</i>

The components and elements inside the chamber have been assigned a number grade in accordance with the following considerations.

- Steel and concrete elements have been assigned 9 points for a report that correctly provides an inspection assessment following the parameters detailed in the analytical rubric.
- Components have been assigned a grade according to the number of images and resolution charts placed in that component. Each image and resolution chart has been assigned a grade of 3 points for a report that correctly provides an inspection assessment following the parameters detailed in the analytical rubric. Since components can have multiple images, the grading per component varies.
- The grade of the component results from a sum of the individual grades of each image and the resolution chart placed in that component. The number of images per component has been presented in Section 3.5.5. The number of images and resolution charts per component is as follows: Component 1 (2 images), Component 2 (5 images), Component 3 (8 images), Component 4 (9 images), Component 5 (22 images), Component 6 (12 images), and Component 7 (18).

The grading score for all the components and elements is presented in Table 4.3.

4.6 Grading Considerations

The evaluation chamber provides performance-based testing under three certification levels. However,

individuals are not required to progress beyond the level they desire consideration. The certification level achieved is determined after a report has been presented for grading.

The UAS must obtain a 70% or greater grade in the first certification level (Level A) to be considered for grading at the next level (Level AA). When Level AA achieves 70% or greater, the grading shall continue to the final certification level (Level AAA).

4.7 Certification Proficiency

The evaluation chamber provides performance-based testing for three certification levels: Level A, AA, and AAA. The levels denote specific capabilities for its successful completion presented below.

4.7.1 Level A

UAS with Level A certification has demonstrated capabilities to do the following.

- Perform routine element-level inspection and general assessment of conventional bridge structures where GPS is generally available throughout the inspection in which the following takes place.
 - Line of sight must be maintained throughout the inspection.
 - Quantitative assessment is not required throughout the inspection (e.g., measurement of crack lengths is not required).

4.7.2 Level AA

In addition to the criteria in Level A, the UAS has demonstrated capabilities to do the following.

- Perform routine element-level inspection and general assessment of bridge structures with more complex geometries, in which the following takes place.
 - Line of sight is generally available at all times but may, at times, require the pilot in command to reposition to recover visibility physically.
 - Inspections require the inspector to provide quantitative data to describe defects.

4.7.3 Level AAA

In addition to the criteria in Level AA, the UAS has demonstrated capabilities to the following must take place.

- Perform inspections where the following are required:
 - collection of highly accurate quantitative data to describe the damage,
 - operation in GPS-denied environments, and
 - operation beyond visual-line-of-sight is not possible.
- Perform inspection providing a qualitative, quantitative, and element-level assessment of complex geometries.

4.8 Report Considerations

After the UAS has concluded the inspection tasks inside the evaluation chamber, a report prepared in post-processing is provided to the proctor for grading and certification. The report will contain the identifier of the element or image inspected inside the chamber with the corresponding qualitative assessment (all levels) and quantitative assessment (Levels AA and AAA). The last two levels also require pictures identifying the defects encountered during inspection.

The proctor proceeds to grade the report using the rubric presented in 4.9 and selecting the certification level achieved following 4.7.

4.9 Analytical Scoring Rubric for Elements

An analytical scoring rubric with grading criteria for components and elements inside the evaluation chamber has been developed. The rubric includes the criteria, descriptor, and score. For convenience, the rubric has been divided into three parts: Part 1 presents the rubric for elements (steel and concrete), Part 2 for images in components, and Part 3 for resolution charts. The rubric has been grouped following the certification levels presented in Section 4.4.

The rubric for elements and components (Part 1 and 2) uses the following abbreviations in each row for conciseness. The abbreviations are as follows.

- “D” followed by a number: qualitative performance-based outcome.

- “A” followed by a number: element-level condition assessment according to the second edition *AASHTO Manual for Bridge Element Inspection*.
- “Q” followed by a number: quantitative performance-based outcome.

In addition, the element-level condition assessment uses the abbreviation “CS” followed by a number that refers to the condition state following the AASHTO manual.

4.9.1 Part 1: Analytical Scoring Rubric for Elements

A table has been developed to summarize the rubric for each element inside the evaluation chamber. The element names correspond to those presented in Section 3.5.2. The rubric has been removed from this report to maintain confidentiality. It remains in the possession of the sponsor states for reference and future implementation.

4.9.2 Part 2: Analytical Scoring Rubric for Images in Components

A table has been developed to summarize the rubric for each image in components inside the evaluation chamber. The image and component numbers correspond to those in Sections 3.5.1 and 3.5.3. The images and rubric have been removed from this report to maintain confidentiality. They remain in the possession of the sponsor states for reference and future implementation.

4.9.3 Part 3: Analytical Scoring Rubric for Resolution Charts

A table has been developed to summarize the rubric for resolution charts inside the evaluation chamber. The rubric has been removed from this report to maintain confidentiality. It remains in the possession of the sponsor states for reference and future implementation.

5. DESIGN AND IMPLEMENTATION OF A UAS ENVIRONMENTAL TEMPERATURE PERFORMANCE EVALUATION

This testing methodology details the data acquisition procedure when UAS hovers under varying environmental temperatures. The test is conducted in an environment without a GPS signal, called the environmental chamber. To be suitable for this testing method, chambers must meet the criteria for minimum distances, temperature, and relative humidity specified in subsequent sections.

The testing is performed in two parts: one under regular environmental conditions and the other under “cold” conditions, as outlined by this document. These parts do not have to be executed on the same day, providing ample time for the chamber to stabilize its temperature between tests.

5.1 Objective of the Performance-Based Assessment

The objectives of the temperature performance evaluation are as follows.

- Determine the performance of small unmanned aerial systems (UAS) under different environmental temperatures.
- Evaluate the ability of the pilot to take off, hover, and maneuver the UAS in different environmental temperatures.
- Record and store flight data generated by the UAS for post-flight analysis.
- Determine the effects of different environmental conditions on the UAS, such as temperature and relative humidity.

5.2 Temperature Considerations

During the test, the environmental chamber must maintain specific temperature and relative humidity parameters.

- For Part 1 of the test, the chamber should maintain a temperature of 70°F (21.1°C) with an allowable variation of $\pm 2^\circ\text{F}$ (1.1°C). The relative humidity should be at 45%, with an acceptable variation of $\pm 5\%$.
- For Part 2, the required temperature is 20°F (-6.7°C), with a variation of $\pm 2^\circ\text{F}$ (1.1°C). Due to the low temperatures achieved in the chamber, no specific relative humidity is set for this segment. However, humidity levels typically range between 50% and 80%.

5.3 Design of the UAS Environmental Temperature Chamber

The test environment's internal dimensions are set to accommodate a typical UAS, considering proximity effects. The chamber's minimum width and length should exceed the UAV's propeller-tip-to-propeller-tip distance by at least 1 foot, providing additional room for the pilot. The height should surpass the UAV's total

height by 3 feet. Figure 5.1 and Figure 5.2 show suggested measurements for an environmental temperature chamber.

5.4 Methodology for the Environmental Temperature Performance Evaluation

The test environment for this method is an enclosed temperature chamber able to set temperature values of at least 20°F (-6.7°C) $\pm 2^\circ\text{F}$ (1.1°C) and 70°F (21.1°C) $\pm 2^\circ\text{F}$ (1.1°C), along with providing a relative humidity between 40% and 80%. The internal dimensions of the test environment have been determined based on the spacing required for a typical UAS. The minimum dimensions of the chamber are as follows.

- Width: greater than the sum of the propeller-tip-to-propeller-tip distance of the UAV plus 1 foot.
- Length: greater than the sum of the propeller-tip-to-propeller-tip distance of the UAV plus 1 foot, and with additional space for the pilot inside the chamber.
- Height: greater than the sum of the total height of the UAV plus 3 feet.

The test is divided into two parts: Part 1 and Part 2. In Part 1, the chamber is brought to normal environmental conditions, while in Part 2, the chamber is set to "cold" conditions. The procedure for both parts is the same, except for the required temperature and relative humidity values.

During the test, the UAV takes off inside the chamber and hovers at a midpoint between the ceiling and the floor. When the UAV separates from the ground, the start time and battery percentage of both the controller and the UAV are recorded. A chronometer is started at the same time. The UAV hovers until the minimum battery power percentage is reached, which may vary depending on the manufacturer.

Once the minimum battery power is reached, the pilot lands the UAV. If the UAV is equipped with software that automatically lands it when the minimum

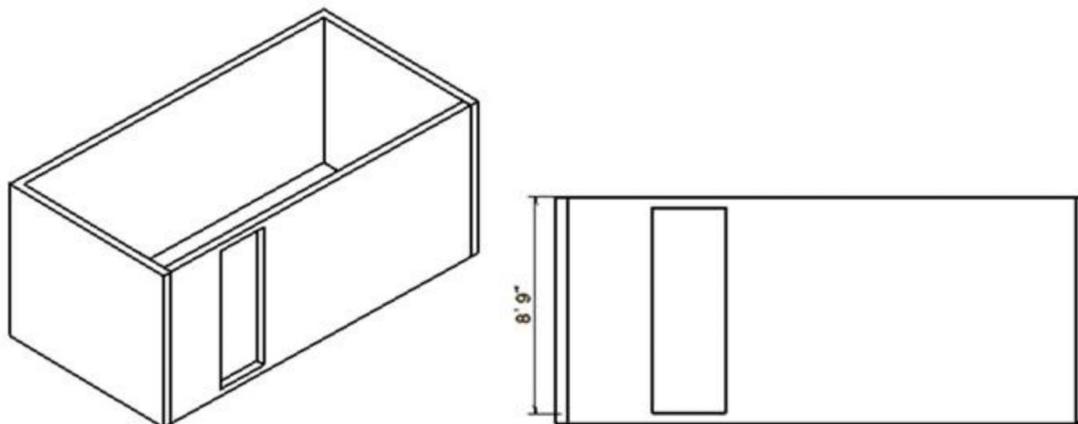


Figure 5.1 Isometric view and elevation view of environmental temperature chamber.

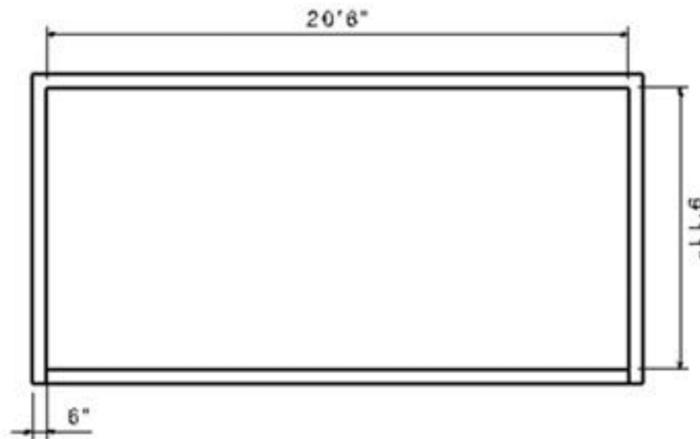


Figure 5.2 Top view of environmental temperature chamber.

Wind Chamber Form

		<u>Date</u>			
<u>UAV General Information</u>			<u>Preflight check</u>		
<u>Brand</u>		<u>Facility</u>	S-BRITE / Purdue University		
<u>Model</u>		<u>UAS comply dimensions / weight</u>			
<u>Registration #</u>		Check the airframe for damage.			
<u>Pilot in Command</u>		<u>Payload/compartments checked</u>			
<u>Battery information</u>	<u>Label number</u>	1	<u>Code</u>		
		2			
		3			
		4			
<u>Test information</u>					
<u>Battery</u>	<u>Start time</u>	<u>End time</u>	<u>Duration</u>	<u>Notes</u>	
1					
2					
3					
4					

Additional Notes:

Figure 5.3 Procedure to report results.

battery power percentage is reached, the landing time is recorded. The test's end time is when the UAV touches the ground. The battery percentage of both the controller and the UAV is recorded, and the chronometer is stopped. The test duration is recorded as the time presented by the chronometer. Figure 5.3 shows an example of a typical report.

If the controller reaches the minimum power percentage before all the batteries have been used, the pilot assesses if it is possible and safe to charge the controller while flying the UAV. If not, the test ends, and this information is noted in the test form. After each landing, the UAV is inspected for any damage.

The test continues with the next available battery until all the batteries have been used and the data has been recorded for each battery.

5.5 Further Considerations and Recommendations

When the pilot in command is unfamiliar with the testing area's temperature and relative humidity conditions, executing trial runs of taking off and hovering in enclosed spaces is recommended. The pilot shall closely focus attention on the behavior of the UAS during the first 15 to 30 seconds after taking off and hovering in place. Based on the author's experience, this time frame

is the most reasonable period for a UAS to show issues related to the conditions of its environment. In addition, the pilot must familiarize himself with the manufacturer's recommendations prior to attempting any operations in temperatures outside normal environment conditions. Hovering is recommended at mid-height between the ground and ceiling but at a distance of no more than 3 feet from the ground to avoid any collision risks inside the chamber.

During beta-testing, the results from this standard for a particular UAS show that flight time differs from what the manufacturer provided. Several parameters can play a role in this difference, and among the most common ones are the age of the batteries, frequent use, weather conditions in previous flights, and complexity of previous UAS missions. During these tests, the results show that exposing the batteries to the same environment under "cold" conditions where the flight operation is going to take place can represent a higher risk of damage to the battery than one that has been kept in warmer temperatures until the start of the flight operation. Therefore, it is recommended that the batteries are only exposed to the environment when used.

An additional payload can increase the risk of damage to the battery. The pilot in command shall always check the manufacturer's specifications before adding an extra load to the UAS. Finally, lighting for night flights, protective cages, and vision devices can significantly reduce flight time. The pilot must account for the additional payload.

5.6 Reporting Results

Figure 5.1 summarizes a brief procedure to report results obtained following the methodology described in this chapter.

6. DEVELOPMENT OF A PERFORMANCE-BASED EVALUATION OF UAS SUBJECTED TO VARYING WIND SPEED FOR BRIDGE INSPECTION

The test method, as part of a comprehensive set of tests administered by the UAS Validation Center, offers crucial insights into the capabilities of UAS when subjected to changing wind speeds. The test is performed in an enclosed space that meets specified minimum distances and geometrical requirements. The data gathered from this test serves as a benchmark for future flights with the UAV under similar payload conditions and wind speeds. The test can be replicated multiple times for varying equipment needs, like those required for nighttime bridge inspections.

6.1 Objective of the Performance-Based Assessment

The objectives of the test are as follows.

- Characterize and evaluate the performance of UAS while hovering under various wind speed conditions.

- Assess the pilot's abilities in taking off and hovering the UAS in indoor environments in various wind speed conditions.
- Evaluate the suitability and preparation of a given UAS when exposed to changing wind speed conditions resulting in turbulence.

6.2 Wind Speed Considerations

This assessment is conducted inside a standard steel 20-foot container or environment with proportions and interior operational characteristics similar to those of the UAS evaluation chamber. The external dimensions of the container are 20 feet in length, 8 feet in width, and 8 feet 6 inches in height.

During the test, specific wind speed parameters are to be maintained. The source of airflow must produce a maximum wind speed of 13.5 knots \pm 2.5 knots (15.5 mph \pm 2.5 mph), as measured 2 feet from its origin. This speed corresponds to level 4 on the Beaufort Wind Scale. Furthermore, while in Zone B, the wind speed from the airflow source should be adjustable.

In Zone A, the airflow should consistently produce wind speeds between 13 and 14 knots, allowing for a fluctuation of \pm 2 knots (equivalent to 15–16 mph \pm 2 mph). The wind speed undergoes variation upon the UAS's entry into Zone B. Its minimum should be half the average steady-state wind speed from Zone A, minus a tolerance of 2 knots (or 2 mph). The maximum speed should mirror Zone A's average steady-state speed plus a permissible 2 knots (or 2 mph). For instance, if Zone A's target speed is 16 knots (~18 mph), then Zone B's minimum should be 8 knots (with a tolerance of -2 knots or 9 mph -2 mph) and a maximum equal to Zone A's (16 knots or 18 mph) plus an allowed 2 knots or 2 mph.

Zone B's wind speed, as shown in Figure 6.1, changes over time. The airflow source should provide the highest wind speed (100%) for 10 seconds, followed by 5 seconds at the minimum speed (50%). This cycle persists until the UAS departs Zone B. The transition between speed changes should not surpass 2 seconds, with an allowable deviation of \pm 1 second. This is illustrated in Figure 6.1.

6.3 Image Quality Considerations

To assess the quality of the images taken inside the wind chamber, copies of the DGK Color Tools High-Resolution Chart, measuring 8.5" \times 11", are positioned on specific chamber components. These resolution charts are typically represented by a rectangular figure with a hatched pattern, as depicted in Figure 3.27. The chart's developer provides techniques for evaluating images containing such resolution charts, though this document does not discuss these methods.

Figure 6.2 illustrates the locations where these resolution charts are placed within the wind chamber. Face F8-1 aligns parallel to the chamber's entrance,

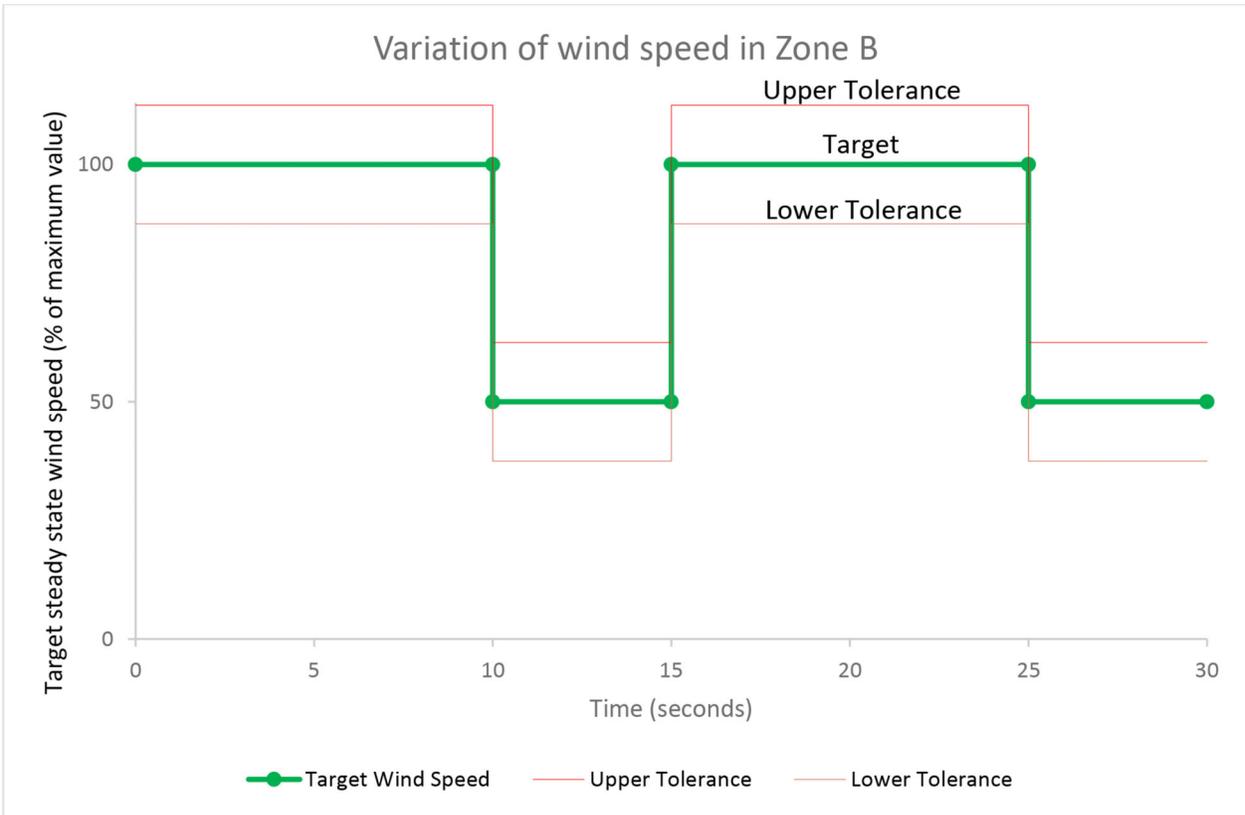


Figure 6.1 Variation of wind velocity in Zone B with respect to time in seconds.

while Face F8-2 sits perpendicular to the entrance and parallel to the divider.

6.4 Geometry Considerations

This test method is conducted inside a standard 20-foot steel container or a space with comparable dimensions and interior functional properties. The container’s external measurements, as outlined in Figure 6.3, are 20 feet long, 8 feet in width, and 8 feet 6 inches in height. This typical cargo container, depicted in Figure 6.4, offers a controlled environment for testing, characterized by limited GPS signal accessibility, regulated lighting, and protection from external wind, rain, and abrupt temperature fluctuations. Using this standardized setting ensures consistent evaluation of UAS regardless of external conditions or location.

The container’s test site should be on an even surface, maintaining a slope of up to three inches across its 20-foot length and 1 inch across its 8-foot width. Additionally, the location should have a nearby power source to run the airflow mechanism, lights, and other equipment inside the container.

The chamber’s design should feature at least one entrance, an unobstructed opening on one of its sides measuring 8 feet by 8.5 feet. As demonstrated in Figure 6.4, this entrance is positioned on the chamber’s left side. The chamber should also contain a full-height

divider, measuring 8 feet 6 inches in height and 10 feet in length, placed 2.5 feet from the chamber entrance’s edge. A landing pad should be set up 2 feet 6 inches from the width’s nearest wall to the divider and 5 feet from the side opposite the entrance. Moreover, an airflow source should be situated at the chamber’s entrance, centralized in the larger area demarcated by the divider.

6.5 Analytical Scoring Rubric for the Wind Chamber

The analytical scoring rubric with grading criteria for tasks inside the wind chamber refers to the rubric developed for resolution charts in Chapter 4, Section 4.9.3. The rubric includes the criteria, descriptor, and score. The proctor will use the same criteria as the resolution chart inside the wind chamber.

6.6 Coding the Varying Speed

The fans are connected to a relay managed by an Arduino. The code used to manipulate the wind changes is presented below. The code starts the system, turns on the fan, and lowers the speed at the indicated time.

```

/*
Turn on fans
Turn on a fan and vary its speed.
*/

```

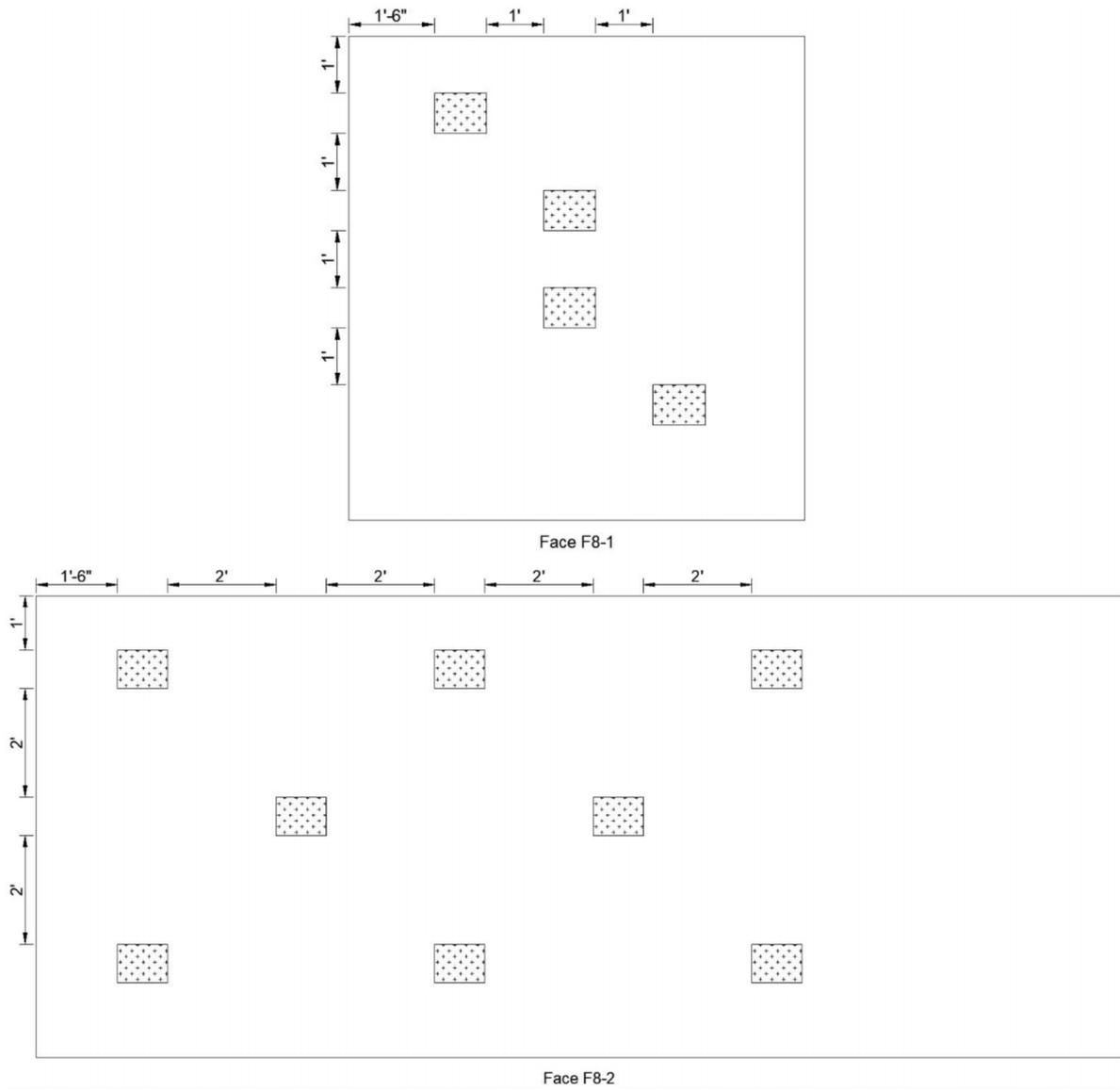


Figure 6.2 Resolution charts in faces of the wind chamber.

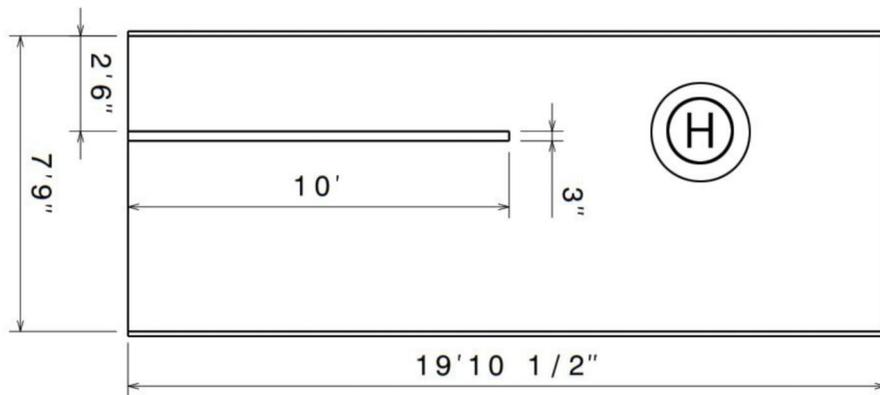


Figure 6.3 Top view of elements inside the wind chamber.

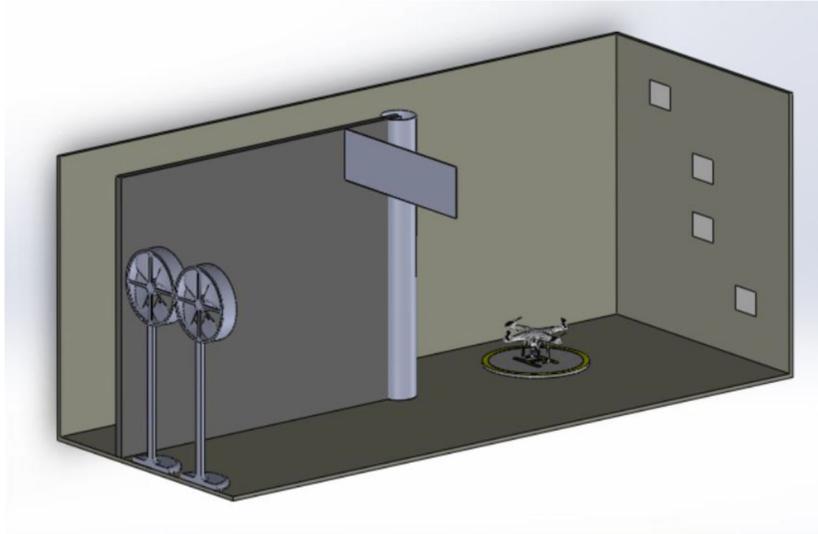


Figure 6.4 General view of the wind chamber.

```
#define powerPin 7
// the setup function runs once when you press reset or
// power the board
void setup() {
  // Pin Mode
  pinMode(powerPin, OUTPUT);
  Serial.begin(9600);
}
// the loop function runs over and over again forever
void loop() {
  digitalWrite(powerPin, HIGH); // turn the fan on (HIGH is
  // the voltage level)
  delay(5000); // wait for a second
  digitalWrite(powerPin, LOW); // turn the fan off by making
  // the voltage LOW
  delay(2000); // wait for a second
}
```

7. DEVELOPMENT OF A FLIGHT CHECKLIST FOR BEST PRACTICES DURING UAS INSPECTION

The flight checklist is part of the performance-based methods to guide a UAS performing bridge inspection. It is a one-page summary of regulations and best practices for successfully completing UAS operations.

7.1 Objective of the Performance-Based Method

The objectives of the method are as follows.

- Provide a concise tool to fill out before, during, and after UAS inspection operations.
- Compile guidelines from the Code of Federal Regulations governing UAS inspection operations.
- Include other guidelines recommended in the literature for inspection procedures when operating UAS.
- Consolidate best practices identified during the development of the performance-based tests in a short format.

7.2 Checklist Sources

The checklist is a compendium of regulatory guidelines and best practices from multiple sources, including the following.

- The Code of Federal Regulations, Title 14, Part 107: Small Unmanned Aircraft Systems.
- The Code of Federal Regulations, Title 49, Part 171: General Information, Regulations, and Definitions (Hazardous Material Regulations).
- Federal Aviation Administration Advisory Circular 60-22: Aeronautical Decision Making.
- Best practices identified in developing the performance-based assessments for the project.

7.3 Checklist Sections Considerations

The checklist has been divided into nine sections, presented below. Each section has an abbreviation in parenthesis for use in future sections when referring to each section.

1. *Mission Information (M)*: General information regarding the pilot in command and flight location.
2. *Airframe (A)*: A review of airworthiness and safety of the aircraft.
3. *Pilot (P)*: A review of the pilot's physical and mental health before flight operations.
4. *Pre-Flight (PF)*: Outdoor flight and data collection considerations before takeoff.
5. *Weather Forecast (W)*: Weather considerations for the flight interval.
6. *Flight Authorization (F)*: Compliance with federal and site-specific requirements when flying inside the desired area.
7. *Flight Details (FD)*: Awareness of aircraft settings, configurations, and emergency plans during flight operations.
8. *Takeoff (T)*: Aircraft airworthiness immediately after takeoff.

9. *Landing/Post Flight (L)*: Considerations after flight operations regarding data collection and airworthiness for the next flight.

7.4 Flight Checklist Sections and Definitions

The expanded checklist version, which includes definitions and a description of each item, is presented below. Each item starts with an abbreviation, as described in Section 7.3, and a number corresponding to its order in the checklist. The description of each item ends with the information source in parenthesis, as presented in the previous section.

7.4.1 Mission Information

^{M1} PIC full name: The name of the Pilot in Command (PIC) certified by the requirements presented in Part 107 of the Code of Federal Regulations. The PIC is the individual directly responsible for the safety and operation of the UAS flight (14 C.F.R. §107.12 & 14 C.F.R. §107.19).

^{M2} Visual observer: The name of the visual observer, as defined by Part 107 of the Code of Federal Regulations, if different from the PIC (14 C.F.R. §107.12 & 14 C.F.R. §107.33).

^{M3} Proposed date of flight: Date of the flight, as required for LAANC approval (14 C.F.R. §107.41).

^{M4} Time range of flight: The approximate flight range/duration. The location and duration of the flight are required for LAANC approval (14 C.F.R. §107.41).

^{M5, M6} Latitude, longitude: The approximate latitude and longitude of the planned take-off position. The exact take-off/landing location is not required; however, it must be within the LAANC request area (14 C.F.R. §107.41).

7.4.2 Airframe

^{A1} Manufacturer's requirements for inspection and maintenance are being fulfilled: Requirements may vary from additional hardware and software checks. Ensure additional requirements are fulfilled when flying over people and vehicles (14 C.F.R. §107.15).

^{A2} Check airframe for damage: Inspection of the vehicle for damage. Visual inspection of parts and structure for cracks, damage, and missing pieces. All flight control surfaces are free to move. Registration markings are visible and properly attached to the airframe (14 C.F.R. §107.15).

^{A3} Motors spin freely: The motors can spin freely on the airframe. No packing material or foreign objects prevent the movement of the motors (14 C.F.R. §107.15).

^{A4} Motor arms secure: Certain vehicles' arms can fold or must be attached before flight. Ensure the arms are locked (14 C.F.R. §107.15).

^{A5} Propellers are attached and free of defects: Propellers are not chipped or cracked. Specific models

require propellers to be attached and/or removed before every flight (14 C.F.R. §107.15).

^{A6} Transmitter and receiver are in working condition: They show no signs of damage or cracks and appear in working order (14 C.F.R. §107.49).

^{A7} Antenna set up/checked: Antennas are unfolded or screwed into the various transmitters or receivers (14 C.F.R. §107.49).

^{A8} Anti-collision lights set up/checked: Anti-collision lights must be visible for 3 nautical miles and flash to provide the PIC location of the UAS for nighttime operations. Night is defined as 30 minutes after the official sunset to 30 minutes before official sunrise, local time (14 CFR § 107.29).

^{A9} Battery connected/secured: The battery is properly connected to the aircraft and secured with various connectors (14 C.F.R. §107.49).

^{A10} Payload attached: The payload is attached to the vehicle. The payload can consist of cameras, transmitters, cargo, or additional sensors to collect data during UAS flights (14 C.F.R. §107.49).

^{A11} Payload operating correctly: Payload in working condition. Any attachments are correctly connected and operating (14 C.F.R. §107.49).

^{A12} Compartment/hatches closed: All compartment covers are closed. Examples are covers for SD cards, USB ports, and payload compartments (14 C.F.R. §107.49).

7.4.3 Pilot

^{P1} PIC is not under the influence of alcohol and has not consumed any alcoholic beverage in the past 8 hours. The individual manipulating the flight controls, PIC, or visual observer has not consumed alcohol in the past 8 hours and is not under the influence of alcohol (14 C.F.R. §107.27).

^{P2} PIC is not under the effect of any drug that affects their mental or physical capabilities: PIC is not under the effect of any physically impairing drug that affects the PIC's mental state (14 C.F.R. §107.27).

^{P3} Are the following negatively affecting the PIC's current physical and mental readiness for flying: illness, medication, stress, fatigue, or emotion? No person may manipulate the flight controls of a small unmanned aircraft system or act as a remote pilot in command, visual observer, or direct participant in the operation of the UAS if influenced by illness, medication, stress, fatigue, or emotion that will negatively impact the safety of the flight (14 CFR §107.17).

^{P4} Is the PIC currently affected by the following hazardous attitudes: anti-authority, impulsivity, invulnerability, macho, resignation? No person may manipulate the flight controls of a small unmanned aircraft system or act as a remote pilot in command, visual observer, or direct participant in the operation of the UAS if operating under anti-authority, impulsivity, invulnerability, machoism, or resignation that will negatively impact the safety of the flight (14 C.F.R.

§107.27 & FAA AC 60-22 Aeronautical Decision Making).

7.4.4 Pre-Flight

^{PF1} Monitor aerial traffic frequencies: To avoid airspace conflicts, it is recommended that radio communications be monitored during departure or during flight operations close to an airport.

^{PF2} Visible hazard check (power lines, etc.): The pilot should be aware of any large obstacles in the flight path, such as power lines, trees, or structures (14 C.F.R. §107.49).

^{PF3} Transmitter on before UAS: Ensure the transmitter is powered on before starting the vehicle. This step prevents runaway or unwanted vehicle behavior.

^{PF4} Vehicle-transmitter connection set: The transmitter and vehicle transmit and receive data. This establishes a communication channel to help prevent signal loss during the flight (14 C.F.R. §107.15 & 14 C.F.R. §107.49).

^{PF5} Camera settings: Optimal camera settings established by the PIC for the mission. Examples are automatic or manual.

7.4.5 Weather Forecast

^{W1} Precipitation probability: Probability of precipitation during the time and day of flight as a percentage. For example, 10% from 3 pm to 5 pm (14 C.F.R. §107.49).

^{W2} Wind speed: Projected steady state wind speed and direction during the time and day of flight. For example, 4–6 mph NE wind from 2 pm to 5 pm (14 C.F.R. §107.49).

^{W3} Wind gusts: Projected wind gusts and direction during the time and day of flight. For example, 20 mph NE wind gusts (14 C.F.R. §107.49).

^{W4} Expected temperature: Forecast temperature during the time and day of the flight. For example, 62°F (14 C.F.R. §107.49).

^{W5} Visibility: Projected visibility. For example, 10 mi (14 C.F.R. §107.49).

7.4.6 Flight Authorization

^{F1} UAS Flight Plan completed and signed: The appropriate agency has completed, signed, and approved the UAS Flight Plan for the flight.

^{F2} Temporary flight restrictions: Temporary flight restrictions (TFR) are in place over the flight area. TFR can be found on tfr.faa.gov (14 C.F.R. §107.47).

^{F3} NOTAMs checked: Notices to Airmen (NOTAM) in place over the flight area. NOTAMs can be found on the FAA website. (14 C.F.R. §107.47).

^{F4} Flight authorizations (LAANC, etc.): Approvals required through LAANC or COA have been completed and approved (14 C.F.R. §107.41).

7.4.7 Flight Details

^{FD1} Flight mode: Different UAS flight modes are available. Models may have modes that turn features on or off or adjust the drone's handling characteristics. List the mode to be used in the flight.

^{FD2} Identify max flight altitude: Maximum flight altitude permitted for the vehicle during the flight operations (14 C.F.R. §107.51).

^{FD3} Obstacle avoidance active: Obstacle avoidance of the vehicle. Vehicles may come with visual or infrared sensors which allow for obstacle avoidance. Obstacle avoidance may increase the safety of the flight but may also prevent the vehicle from entering restrictive environments. It is critical to be aware of whether obstacle avoidance is active or inactive to pilot the UAS properly.

^{FD4} Tether distance set: The maximum distance the vehicle is allowed to fly from the home point or the controller. Tether distance can prevent the drone from entering areas that are not considered in the flight plan.

^{FD5} Signal lost plan: Whether vehicle and controller connection are lost determines the selection of a specific mission abort procedure. Common procedures are to return to home and land, hover in position, and land at the current location.

^{FD6} Battery failsafe plan: Certain UAS have intelligent low-battery systems where the flight system can determine the battery required to land safely at the take-off location.

^{FD7} Visual line of sight plan: A plan for observing the vehicle visually during operation (14 C.F.R. §107.31).

7.4.8 Takeoff

^{T1} Takeoff/landing point identified: A suitable take-off and landing point far from large structures, trees, or other obstacles (14 C.F.R. §107.49).

^{T2} UAV is on stable, level ground: Placing the vehicle on stable ground will allow for a smooth vertical take-off and provide the system with an adequate initialization point for inertial measurement systems.

^{T3} Area around UAV is clear of obstructions: Ensure that there are no ground hazards that can prevent the vehicle from taking off (e.g., tall grass) or hazards that the vehicle could collide with during take-off (14 C.F.R. §107.49).

^{T4} Hover for 15 seconds after takeoff: Hovering the drone in the same location for a given period allows for a check to ensure the system's onboard measurements are operating properly.

7.4.9 Landing/Post Flight

^{L1} Camera in landing position: Certain drone models require the camera to be in a specific position, such as straight down or parallel to the ground, to avoid damage or aid in landing.

^{L2} UAV off before transmitter: Ensure that the vehicle is off prior to turning off the controller to prevent a flyaway of the vehicle.

^{L3} Data downloaded: All data has been removed before the aircraft's disassembly. This may also be required if performing multiple flights on one SD card to prevent the storage space from completely filling up.

^{L4} Batteries properly stored: Batteries are stored and managed according to the manufacturer's recommendations. Lithium Polymer (LiPo) batteries are considered hazardous and should be stored accordingly (49 C.F.R. §171.8).

^{L5} Airframe checked, cleaned, and stored: the Airframe is inspected post-flight and cleaned, as necessary.

^{L6} Flight log updated: The pilot and vehicle flight logs are updated with the previous flights and the number of cycles performed on the batteries.

7.5 Final Flight Checklist

The final checklist is presented as an appendix due to the modifications made to fit all the content on one page. The checklist also comes with an explanation for all the terms included in Section 7.4. The checklist is intended to be a simple field tool; therefore, the explanation may not always be necessary. The explanation from the previous section can be reviewed a couple of times in the office and is not needed in the field.

8. BETA-TESTING OF PERFORMANCE-BASED ASSESSMENTS

The final version of the performance-based assessments developed in this project is a result of constant revisions and feedback provided by multiple representatives from state partners, industry companies involved with UAS bridge inspection, the United States Army Corps of Engineers, and the Federal Highway Administration. The following section describes the methodology for collecting feedback and summarizes modifications implemented after a careful review of comments provided during beta testing.

8.1 Objective of the Beta-Testing Phase

The objectives of the beta-testing phase are as follows.

- Collect feedback from bridge inspection experts on the components and elements presented in the performance-based methods to achieve an authentic assessment.
- Revise and modify elements and components in the assessment that do not resemble bridge inspection scenarios.
- Calibrate and revise the rubrics provided for each performance-based assessment based on test-taking experience from the beta-testers.

- Verify the connection between performance goals and performance testing for each assessment this project provides.
- Capture feedback from infrastructure owners, regulatory bodies, and industry UAS users regarding performance-based testing.

8.2 Beta-Testing and Feedback Considerations

Feedback was collected in two ways: verbal and written feedback.

8.2.1 Verbal Feedback

Verbal feedback was anecdotal comments from each of the beta testers before, during, and after each test. The author compiled spoken feedback in digital documents for future review and analysis. The beta testers knew this data collection would be used for research purposes. Verbal feedback snippets are presented in the next section.

8.2.2 Written Feedback

An instrument was developed to collect feedback and facilitate beta-testing of each performance-based assessment developed for the project. The instrument, a survey, was presented to them after the conclusion of all the tests. The instrument requested the following information from each of the participants.

- General information: name, gender, date, and employer.
- Background information: bridge inspection experience, training courses relevant to bridge inspection, Part 107 license, use of corrective lenses, experience with routine, hands-on, and UAS inspections.
- Before the study: quality and usefulness of the chamber videos.
- During the study: the following were collected: drone brand, payload, confidence level inside the chamber, effort level, focus level, lighting conditions, GPS signal, controller use, quality, and quantity relevance of the components, flying experience, material quality, and image quality.
- After the study: rate their flight performance, experience seeing the elements closer after the tests have concluded, and fairness in the assessment.
- Post-processing: post-processing experience, length of post-processing, and computer programs used.
- Additional feedback: further written feedback in narrative form.

8.3 Summary of Feedback

The following section summarizes relevant findings in the feedback responses during beta testing. The providers of this feedback include the following.

- Representatives from state partners who completed the performance-based assessments.

- Representatives from state partners who received updates on the project.
- Representatives from non-state partners who received updates on the project.
- The United States Army Corps of Engineers.
- Industry companies using UAS for bridge inspection.

8.3.1 Summary of Feedback and Implementation in the Assessments

Verbal and written feedback was collected from conversations and surveys from beta testers and presentations to state partners. This feedback was compiled in written documents, and relevant feedback was analyzed and applied when relevant. Some feedback has been summarized below in italics, followed by the executed action item.

“The most difficult part of flying a drone is looking beneath the deck at floor beams/stringers. More emphasis should be put on looking and flying UP into obstacles and not DOWN into obstacles.”

“The MOST challenging and high-risk (to the drone and data) activity is flying beneath the bridge deck over water. It is also usually the most difficult and expensive to inspect via rope access or snooper. (...) More focus should be put on certifying drone pilots for this specific environment and less for those easy to climb or aerial lift accessible trusses.”

The evaluation chamber was adapted to include Component 4 and 6 accounting flight experiences to look up and down. Steel elements were also added in multiple locations to provide the experience of inspecting a bridge deck, including the wind chamber.

“It would be helpful to see the course before flying”

“[Additional information regarding the evaluation chamber you wish had been provided] Maybe examples of damaged and undamaged components.”

“Any info prior to flight to help with spatial awareness is beneficial including plans, photos, videos, walkthrough, etc.”

A video was developed to incorporate the idea of “seeing” the course before the test.

“Place sonotube at end of wall to replicate pier wall and place one tag on the end and one slightly on the corner away from the fans. Place false beam across ceiling at end of wall and place photo on downwind side making them stall, near the bottom on the backside.”

This idea was completely implemented in the wind chamber elements.

8.3.2 Summary of Quantitative Feedback and Analysis

The instrument was collected after the feedback was provided, de-identified, and summarized for consideration.

8.3.2.1 Performance-based assessment objectives.

The instrument collected feedback on applying the

objectives of the performance-based tests. The objectives are presented in the section but are repeated below for convenience.

- Develop a repeatable test a UAS must complete to qualify before inspecting civil engineering structures.
- Establish an environment for the test based on constraints and challenges when conducting bridge inspections.
- Assess UAS inspection capabilities by identifying steel and concrete defects inside the environment developed for the test.

Objective (a) was assessed with the following question.

- How repeatable do you consider the evaluation chamber?

Repeatability can be defined as the ability to fully replicate the evaluation chamber in any part of the United States by having components or elements that are relatively easy to find or build.

As depicted in Figure 8.1, 100% of the respondents answered that the evaluation chamber is repeatable, with 82% considered very repeatable and 18% moderately repeatable.

Objective (b) was assessed with the following questions.

- What was the GPS signal registered by the UAS inside the evaluation chamber?

- How did the lighting inside the evaluation chamber compare to a typical bridge inspection?

- How would you rate the relevance of the components and specimens inside the evaluation chamber when performing bridge inspection?

A 1 means they were not relevant, and a 10 means they were highly relevant

Repeatable

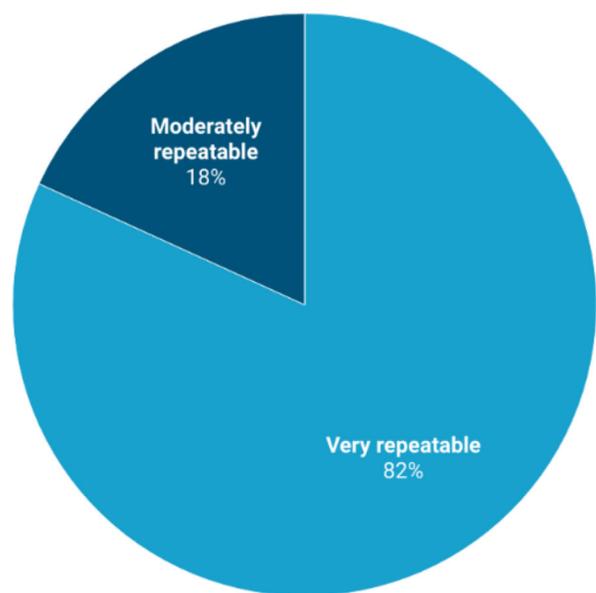


Figure 8.1 Feedback results on repeatability.

- How would you rate the variety of components and specimens inside the evaluation chamber compared to the bridges you inspected?

A 1 means they represent a low variety of bridge elements, and a 10 means they illustrate a wide variety of bridge elements.

Of those surveyed, 50% reported a very weak signal, and 50% reported the absence of any signal inside the evaluation chamber. In addition, 89% of the participants reported similar lighting inside the chamber, and 11% reported less lighting than a typical bridge inspection. Both questions are summarized in Figure 8.2. Finally, almost all of the participants graded between 7 and 10 out of 10 on the relevance of the components and between 8 and 10 on the variety of the components inside the chamber, as presented in Figure 8.3.

Objective (c) was assessed with the following question.

- How would you rate the experience of flying around the components inside the evaluation chamber with respect to your previous bridge inspection experience?

A 1 means flying inside the chamber did not remind you of anything you have seen in past bridge inspections, and a 10 means they heavily reminded you of elements you have seen in past bridge inspections.

As presented in Figure 8.4, 83% of the responders provided a grade higher than 7, with 50% grading the experience between 9 and 10, showing a strong resemblance to previous inspection scenarios.

Among the specific design features of the evaluation chamber lies the capability to shield the test from the influence of external factors, such as the environment.

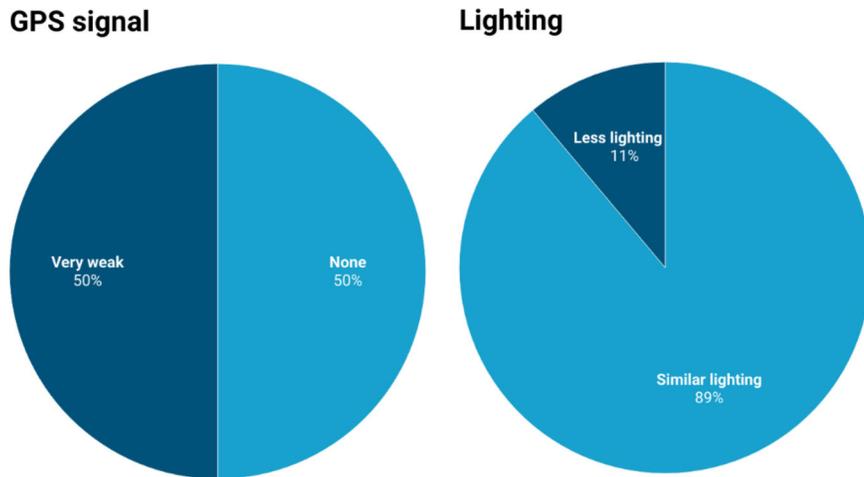


Figure 8.2 Feedback results on GPS signal and lighting conditions.

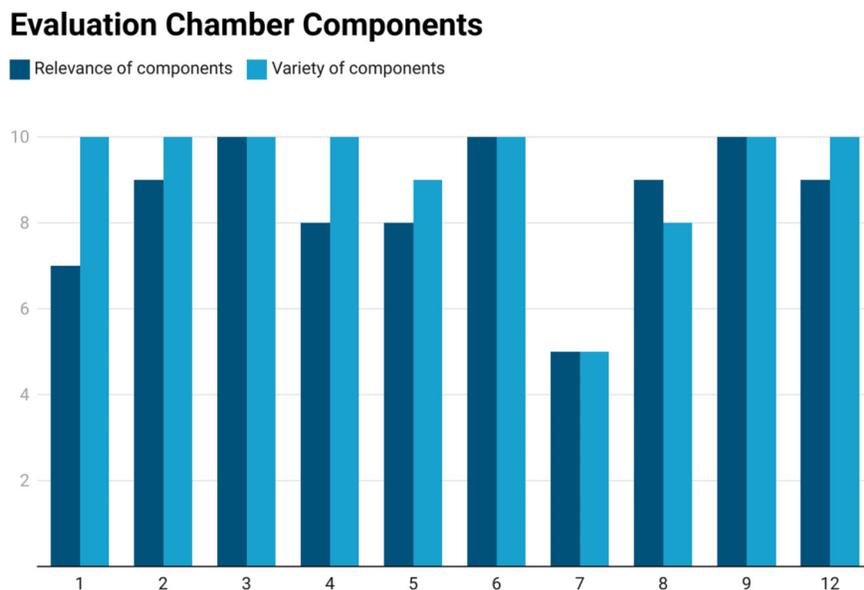


Figure 8.3 Feedback results on component relevance and variety.

Flight compared to previous inspection experiences

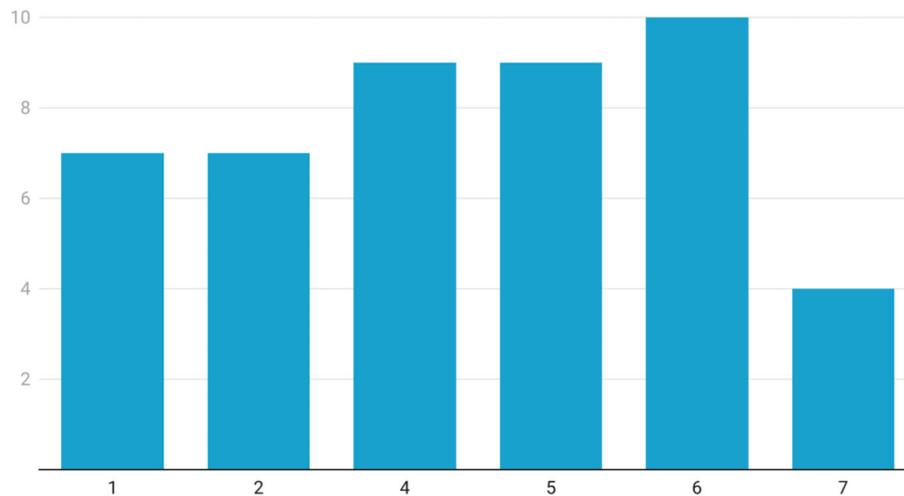
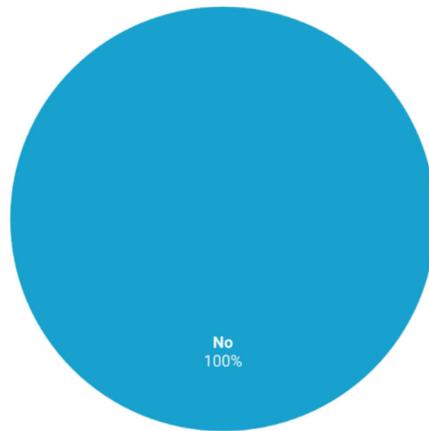


Figure 8.4 Feedback results on flight experience inside the chamber compared to previous inspection experiences.

Precipitation interference



Wind interference

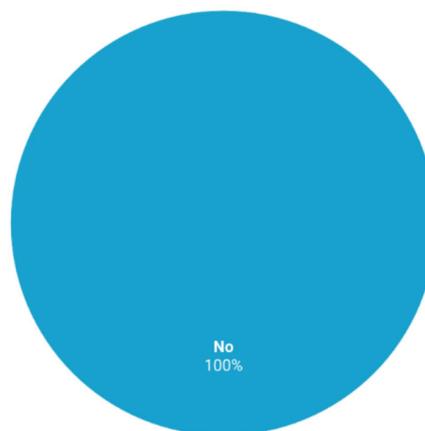


Figure 8.5 Feedback results on precipitation and wind interference.

Beta-testers were asked whether precipitation or wind interfered with their test, with 100% responses indicating “No” for both questions, as presented in Figure 8.5.

The latest versions of the test included a pre-test video explaining the elements and objectives of the test. The beta testers were asked to rate the quality and usefulness of the video. As presented in Figure 8.6, 100% of the testers agreed that the video helped understand the goals of the test successfully and was of high quality.

Furthermore, the testers were asked to rate their performance before (rate your confidence in completing the study) and after (rate your performance). Most of the testers rate their performance after the test higher than their level of confidence before the test. In addition, almost 90% of the testers described the test as a fair assessment of their UAS inspection capabilities, as presented in Figure 8.7.

Similar feedback was collected for the wind chamber and the practical test and is summarized below. As presented in Figure 8.8, 100% of the beta testers considered the wind chamber to be repeatable and a fair assessment of UAS inspection capabilities in environments under wind changes. Similarly, beta testers considered the practical test to provide a similar level of effort compared to performing UAS field inspections and fairness of the test, as presented in Figure 8.9.

Finally, quotes summarizing the success of these assessments are presented below. These quotes summarize the general feedback provided by the beta testers.

“I certainly think it is [a] FAIR [assessment].”

“I believe the [evaluation] chamber is a very helpful tool for bridge inspection”

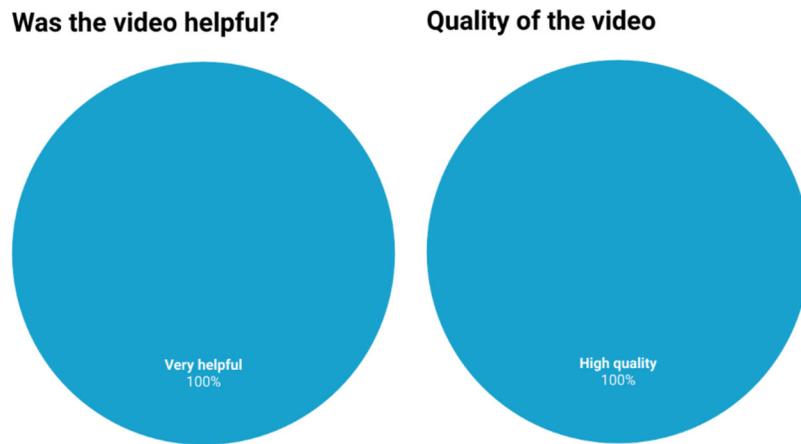
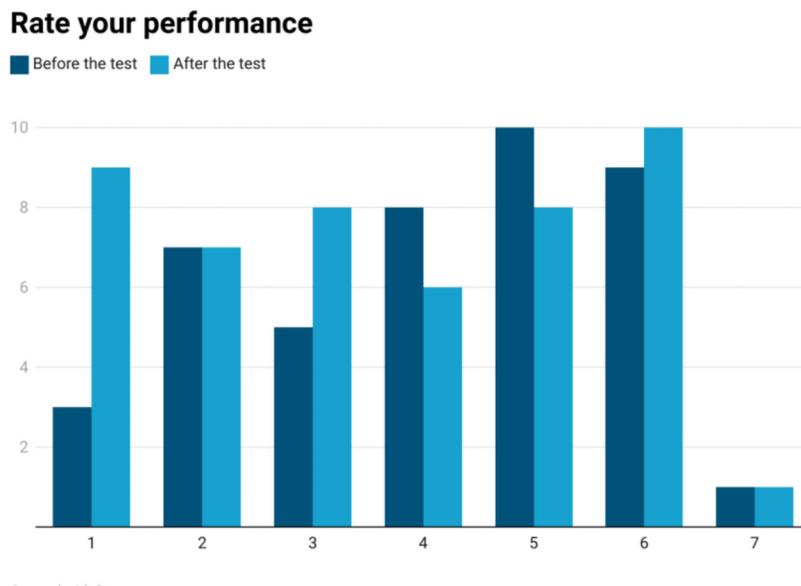


Figure 8.6 Feedback results on the video quality and usefulness.



Is the Evaluation Chamber a fair assessment?

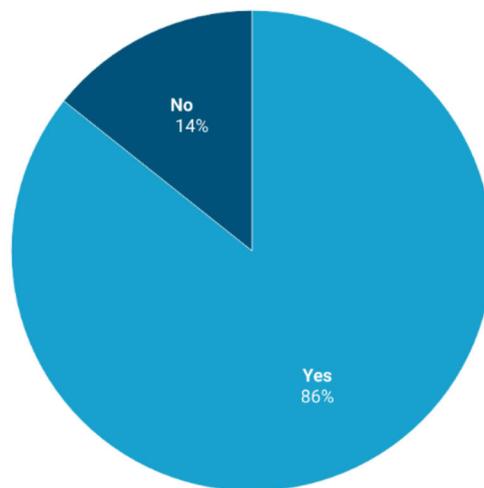
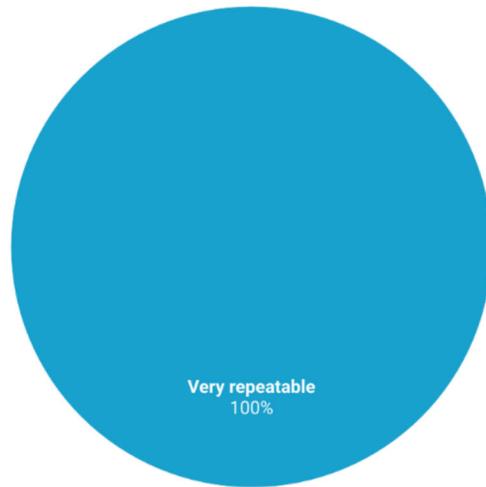


Figure 8.7 Feedback results on performance and fairness of the test.

Wind Chamber Repeatability

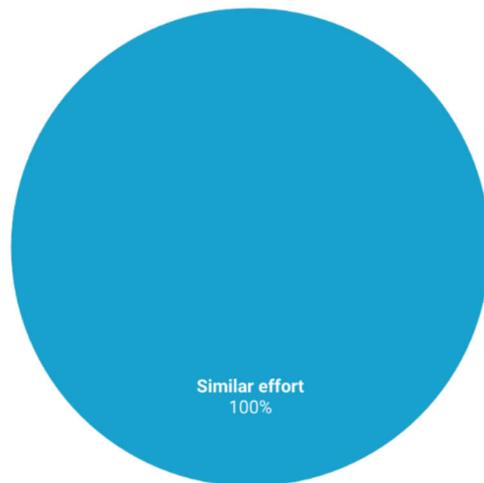


Is the Wind Chamber a fair assessment?



Figure 8.8 Feedback results for the wind chamber's repeatability and fairness.

Practical Test Level of Effort



Is the Practical Test a fair assessment?

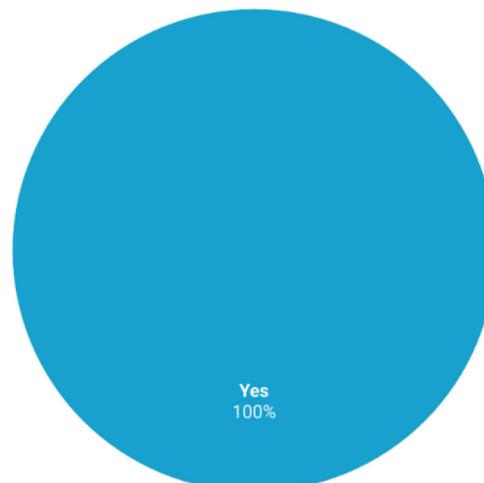


Figure 8.9 Feedback results of the practical test when measuring level of effort and fairness.

"Lighting on one side did nice job simulating sunlight"

"Good amount [of lighting], required I fly back and change batteries"

"The practical test is representative of a UAS bridge inspection – involving all aspects and challenges associated with these activities."

9. CONCLUSIONS

9.1 Conclusions

This study established a structured approach to evaluating unmanned aircraft systems (UAS) for bridge inspections, culminating in developing performance-based assessments and methodologies for this technology. The comprehensive performance-based testing

developed in this work offers a robust methodology to evaluate UAS applied to bridge inspection under various conditions. These tests ensure that UAS are reliable, safe, and efficient, especially for critical operations. The design of the test environments, coupled with the diverse set of conditions under which the UAS are evaluated, can provide a clear view of their real-world applicability and performance capabilities.

The evaluation chamber test targets UAS adhering to specific weight and dimension requirements. Following the identified limitations in the original design, the chamber was updated to include a mix of image-based components and actual steel and concrete specimens replicating real-life bridge defects. Additionally, the inventory of images within the chamber

was refined, eliminating redundant images and updating existing ones. Certification levels from this test range from Level A to Level AAA, indicating the UAS's capability to identify findings correctly. During the test, the pilot must control the UAS outside the chamber, ensuring they inspect all the elements within. Post-test, the evaluation hinges on the UAS's ability to successfully identify all potential defects within the chamber via real-time observations or subsequent analysis. The chamber was proven successful at recreating bridge inspection experiences, allocating a test in a controlled environment, and being repeatable. The chamber was also highly rated as a fair and objective assessment.

The environmental temperature chamber is a testing methodology designed to evaluate the performance of UAS under different environmental temperatures. This test is conducted in an environmental chamber that lacks GPS signals. This chamber is divided into two testing parts: assessing performance under regular conditions and under "cold" conditions. The main objectives include understanding how different temperatures affect the UAS's performance, assessing a pilot's capability in varying conditions, recording flight data for post-flight analysis, and identifying the effects of temperature and relative humidity on the UAS.

The wind chamber is conducted in a controlled environment that meets specific geometrical requirements. The primary objective is to evaluate the UAS' stability while hovering in diverse wind speeds, gauge the pilot's proficiency in managing the UAS under these conditions, and determine the system's adaptability to wind-induced turbulence. During the test, wind speeds are closely regulated. Zone A of the test chamber maintains steady wind speeds between 13 and 14 knots, while Zone B features variable speeds. In Zone B, the airflow alters between a maximum speed and half of that every 10 and 5 seconds, respectively. Another essential consideration is image quality, assessed using DGK Color Tools High-Resolution Charts placed inside the wind chamber. The chamber was effective in assessing the UAS's ability to fly under variable wind and recreate inspection scenarios where the UAS is affected by wind.

The practical test assesses UAS bridge inspections using existing bridges and a standard methodology. It provides three types of certification levels and demonstrates the importance of real-world testing, requirements for UAS capabilities, and the opportunity to analyze defects in outdoor settings. Considering the beta testing results, the practical test proved to be repeatable and a fair assessment.

The flight checklist summarizes regulations and best practices for inspectors before, during, and after UAS inspections. It is a compendium of the experiences collected throughout the project and the changes in regulations throughout its execution. The checklist provides easy-to-access information when flying and alerts the users of potential weak points in the flight plan.

Finally, this work summarizes methodologies recommended for infrastructure owners to apply before UAS is used for inspection. The author strongly recommends its implementation on a large scale in all regions of the United States. Some implementation scenarios can include training before testing and a thorough review of the UAS authorized to provide information from infrastructure. Implementation will allow us to safeguard this technology's use and our communities' safety. These assessments are the next step towards safe and resilient infrastructure.

9.2 Future Work

The assessments reflect years of work surrounded by an ever-changing environment. The first idea of the evaluation chamber appeared in 2019 and has been continuously revisited and updated. Future work should stay vigilant about the current trends of the UAS market and consider possible modifications for new vehicles and technologies. Incorporating AI in some platforms can improve some of the aircraft's capabilities and can be seen as a threat to the integrity of the assessment. However, the assessment must always consider the final goal of inspection and will most likely remain unchanged.

Additional work can establish the effect of natural hazards and post-disaster environments on UAS. This platform has been increasingly used in reconnaissance missions, and future assessments should evaluate its feasibility in identifying objects, navigating saturated environments, and determining the effect of changing climate on the vehicle. Wind tunnels and fieldwork may play an important role in this assessment.

Finally, future work should focus on developing training modules and materials for future users of these assessments. Field and online workshops can be great tools for disseminating the capabilities of this project's deliverables and training future proctors. Testing agencies can also develop specific material for their testers prior to the assessment: videos, handouts, audio recordings, and more. The implementation of these assessments will guide the material required for their success.

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APPENDICES

Appendix A. Commentary on the Performance-Based Assessments

APPENDIX A. COMMENTARY ON THE PERFORMANCE-BASED ASSESSMENTS

The following appendix summarizes the reason behind some of the performance-based assessments presented in this document. This section is written in commentary form to illustrate further some of the principles followed when making design decisions for all the assessments. This appendix provides further background on the sound engineering and decision-making followed in its development and clarifies fundamental questions when this project is implemented. This section follows the same chapter order.

Introduction

UAS: The introduction provides multiple definitions for UAS, including Uncrewed Aircraft Systems. The FAA introduced this recent term in 2021 to promote a more inclusive industry (Federal Aviation Administration, 2021). However, the literature has not widely adopted the term yet, and many documents still use unmanned or drone. This document recognizes the need for an industry-wide adoption of the term and uses UAS when referring to the system and UAV when referring to the vehicle.

Literature Review

UAS in infrastructure applications: UAS can have multiple purposes, and some of the applications can be different from the ones the manufacturer intended to use them for. Therefore, the UAS considered in this section are based on the reported use of the platform in operations involving infrastructure and the criteria of the author based on the experience of state partners, industry representatives, federal government representatives, and other beta-testers.

Chapter 3: UAS Evaluation Chamber

Small UAS: All UAS used in bridge inspection fall under the FAA category of small. The weight requirements are compared against the UAV weight plus any additional payload.

“Best” images in the image inventory: This chapter mentions how the best images among multiple of the same object were chosen for the final version of the chapter. Best is defined as pictures with the best quality, covering the important features of the element, with no reflected lighting, providing enough context to the inspector, and adequate size to fit in the chamber.

Why three levels? The number three comes from the objective of providing certification for routine and NSTM (hands-on inspections). However, a routine inspection can have different difficulty levels depending on the bridge inspected, e.g., shorter or longer spans, over a body of water or roads, complex geometries, etc. Therefore, routine is considered to occupy two levels, and hands-on is the last one. In a larger controlled environment, e.g., larger than 40 feet, there is a possibility to even provide further levels within these three. However, this would complicate the assessment and may not add value. The author recommends three levels.

Why A, AA, or AAA? In engineering education, numbers and letters of the alphabet are empirically related to a feeling of better or worse performance. From the early stages of our academic journey, engineers have learned to relate that A is better than C, and 3 is more complex than 1. In some cases, such as races or competitions, 1 is “better” than 3. The certification levels in these tests do not imply that someone who attained them is “better” than others but instead that they are qualified for different purposes, e.g., routine or hands-on. Therefore, the author decided to borrow terminology from credit ratings in the banking industry: A, AA, AAA.

Component 1: This is the second element the author developed in response to forcing UAS inspectors to fly low, as in many bridge inspections. It is just a 2-foot by 3.5-foot rectangle. The

additional face in the bottom helps the element stand and can be replaced by any other element that helps the component hold itself in place. The dimensions are mainly chosen to force a low fly of most UAS and fit in the chamber's entrance.

Component 2: This is the first element the author developed in response to having a flat surface to inspect defects. The component forces the UAS to scan along the longer face or rotate the camera at least 90°. Like Component 1, the bottom face is just for the element to stand by itself. The component is as tall as it is on purpose: tall enough to cover most of the chamber's height and leave 1 foot of clearance to allow light to enter through its entrance.

Component 3: This element was designed for areas where the UAS has to scan round surfaces, forcing a flight in a tall member. This component was placed in the chamber's center in earlier drafts to provide complete inspection access. However, inspecting round elements with limited access (less than 360° access) is more common and challenging. The height is the same as that of Component 2, following similar considerations (as tall as it can be).

Component 4: This element was designed for various purposes: inspection on the roof and floor, blocking and against light on the side faces, and entrance and exit areas. This component was longer (>4 feet) in depth. However, the dimension was adjusted to the minimum that the typical UAS would be completely covered by the roof and still able to maneuver. The height is similar to Component 1.

Component 5: This element was designed as a reminder of complex geometries in trusses. This is the most complex element inside the chamber as it has two K frames, and images are placed in multiple faces. This component was a cross frame in earlier versions of the chamber. However, K frames offer the same surfaces and challenges as cross frames with the added benefit of larger dimensions where the UAS can navigate and still reflect field conditions. The dimensions were adapted to follow the typical UAS dimensions. This component also had images in the slender elements in earlier versions but was removed from the final version since it was determined that this bridge inspection experience could be achieved with Component 2.

Component 6: This element started as a variation of Component 4 and, at some point, was considered to replace it. However, further studies showcase how this element provides an additional challenge: vertical inspection when a roof is in place close to the UAS. In addition, the component's height, similar to Component 2, allows for placing larger images in each face than other components.

Component 7: This element has features from Components 3 and 4. This element provides spaces where multiple elements convey in one point and difficult access. This component is also considered the “full hands-on” component since inspection at certain angles would require such inspection. This component was also designed to account for requirements beyond the visual line of sight. When this document was written, the FAA did not allow operations beyond the visual line of sight except for waiver requests. However, the author recognizes that this industry is rapidly changing and can change in the future. Therefore, the author designed this component to be movable. Currently, the component challenges the operator to maneuver by relying on the controller, more representative of bridge inspection operations. If full compliance is required, the opening can be rotated to face the chamber's entrance and fully meet requirements beyond the visual line of sight.

Elements S1-S15 and C1: All the steel and concrete elements were obtained from the S-BRITE facility at Purdue University. These elements can be replaced by similar elements that comply with the considerations described in the chapter. The elements were chosen to provide representative defects, shapes, and dimensions in bridge inspection. Some were torched to fit in

the chamber (S2), others were arranged in the faces of the container (S12), and some look similar but present different defects and locations (S10 and S11).

Resolution charts: The resolution charts can be purchased on online stores (Amazon) or reproduced on high-quality paper. The charts are standard, and the literature provides several options. The one selected in the final version of the chamber has the following features: it presents color and black and white, contains lines and circles, sturdy material, is inexpensive, and has letter size.

Images: Multiple materials were tested in developing the images used in this study (this could be a thesis by itself), looking for a final product that was sturdy, durable, portable, and high-quality. Earlier versions of the images only consisted of the printed image pasted with tape over the component. However, this would move every time a UAS flew next to them, no matter how much tape was used. The final version used the following materials: Poster Board Heavy Weight White 22 in × 28 in by Pen+Gear (Walmart), pasted to the image with a layer of Loctite Spray Adhesive General Performance Lightweight Bonding (Menards), and held to the component by Velcro Sticky Back General Purpose 15 ft × ¾ in (Menards). All of the images were printed using HP DesignJet XL 3600.

Image location: The images have been carefully placed in their location following the guiding principles: fit on the face, maximize use of the space, places where it is likely a successful inspector would look, and variety. When changing the image set, make sure to follow the same guidelines provided in this work.

Lighting: Capa Salinas (2021) summarizes the reasoning behind adding lights. Briefly, lights make the environment more realistic and provide another testing point when taking pictures facing or opposite the light. The lights used are 44" LED Shop LT 5500LM, color rendering index ≥ 80 .

Aeration inside the chamber: The container can become humid or retain odors, particularly if used. A solution is to add at least two vents: one in the front and one in the back. These vents should not affect the UAS's performance when testing.

What if...

the UAS evaluation chamber was located 50 feet above the ground? The author considered this version of the chamber but concluded that prohibiting operator access to the chamber would achieve the benefit of restricting access by having it that high.

the UAS evaluation chamber has fans blowing at the elements? The author considered this version but concluded that separating the difficulty of navigating complex geometries from wind effects. Therefore, both are tested in separate chambers.

the elements inside the UAS evaluation chamber were not inside a container? This is a feasible idea for implementation when a container is unavailable, or emergency procedures require retrieving the UAS from the sides. However, for this version, the container is ideal in limiting GPS signals and simulating the large distances where the operator has limited access in an inspection.

the UAS evaluation chamber only has "real" objects or only components? It is not possible for a single owner or testing agency to have available all the defects assessed in the final version of the chamber. Therefore, a combination of both comprise an authentic assessment.

my UAS does not fit in the chamber? The chamber was designed to fit most UAS used in infrastructure applications. If the UAS does not fit in the chamber, this vehicle may have trouble navigating complex geometries over far distances. Proceed cautiously when flying near bridges over water or between steel or concrete elements.

I want my UAS to fit in the chamber? The chamber's dimensions and the typical UAS selected in this work are relative to each other. If a UAS larger than the typical one needs to be accommodated, the chamber can be scaled to a factor in relation to the desired and typical UAS. However, the chamber has stopped being standardized, and the performance-based outcomes must be redefined. Proceed with caution.

I permanently place the pictures inside the UAS evaluation chamber? The container will likely be placed in an outdoor environment, and the constant changes in temperature will damage the material. Velcro helps to attach and detach before and after each test when they happen on different days.

Chapter 4: Standard Grading Assessment

NHI guidelines: This assessment was developed using the NHI Evaluations and Assessment considerations. The NHI is well-known in this field and has been developing assessment content for decades. Its guidelines match what multiple educational authors agree are best practices in developing this type of assessment and the outcomes mentioned by ABET.

Certification level considerations: The colors were selected based on the same reasoning as the level name: distance from the belief of better or worse. Therefore, the colors present neutral elements to delimit each area.

Scoring: The elements are graded over nine, and images and charts are graded over three. There are a variety of reasons for that. First, the grade must be a multiple of three, so the rubric can be split into three areas (plus zero grade). Second, beta-testing demonstrated that these numbers provide a large range to assign in-between values when grading. Third, the number can be modified for convenience as long as it remains consistent (changing one to nine changes all of them) and the total is converted to 100.

Nine points versus six versus three: The rubric presents three descriptors, plus zero, to assess different levels of completeness. Nine points correspond to the successful assessment of that element. Six points relate to either A (AASHTO) or D (description), following the reasoning that successfully determining the AASHTO description would indicate the basics of the assessments in a field inspection. In addition, determining the description would provide enough context to understand the damage condition, if any. Three points relate to only the descriptor, as only meeting these requirements in the field would be enough to infer the rest but not good enough to obtain six or nine points.

Score colors: The rubric uses neutral colors to distance from the belief of good or bad grades.

Chapter 5: Environmental Temperature Chamber

Why 20°F and 70°F? The state sponsors mentioned these two temperatures during the kickoff meeting to represent “cold” and “room temperature” conditions. However, the procedure is the same for any temperature the testing agency selects.

Am I expected to buy a chamber? No. Chamber that manipulates temperature is everywhere. This work found chambers with owners willing to lend for research purposes in meat processing plants and academic institutions.

Chapter 6: Wind Chamber

Higher wind speeds: The highest wind speed in the chamber follows the value in Level 4 of the National Weather Service. Higher levels of field inspections are not possible or not safe to

conduct. However, if higher wind speeds are needed, the testing agency can modify the speed and adapt the 50% value.

Alternating wind speed values: The chamber was designed to change from high wind speed to 50% of that value. This change was made possible using the Internet of Things (IoT) Relay (AC/DC Control Rel) manufactured by Digital Loggers Inc., which uses the two “normally OFF” outlets. This relay was controlled by an Arduino UNO R3 Board using the code presented in the chapter.

Chapter 7: Flight Checklist

One page: The checklist was designed to fit on one page. In that process, it omitted certain aspects that some pilots or inspectors must consider essential in their day-to-day operations. The checklist is intended to present minimum requirements and does not pretend to be a holistic review. The UAS must always follow FAA, governing entities, and local and state regulations. The pilot must always follow the manufacturer’s recommendations.

Chapter 8: Beta Testing

Alpha testing: Rounds of alpha testing and versions of the test before the final versions were conducted but are not reported in this work. Alpha testing consisted of verifying the image material, visual inspection of the images used, experience using the images instead of steel and concrete specimens and comparing components to bridge experiences.

Beta tester participation: Beta testing for this project involved inviting participants to the Purdue facilities, traveling from in and out of state, working a full day in the field, and filling out the feedback survey.

Project Partners

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Drone pilot during the practical test at the S-BRITE facility.

Publication

This report was published in collaboration with the Joint Transportation Research Program and Purdue University. The full content of this technical report is available for download at <https://doi.org/10.5703/1288284317910>.

Open Access and Collaboration with Purdue University

The Indiana legislature established the Joint Highway Research Project in 1937. In 1997, this collaborative venture between the Indiana Department of Transportation and Purdue University was renamed as the Joint Transportation Research Program (JTRP) to reflect state and national efforts to integrate the management and operation of various transportation modes. Since 1937, the JTRP program has published over 1,800 technical reports. In 2006, the JTRP partnered with the Purdue University Libraries to incorporate these technical reports in the University's open access digital repository and to develop production processes for rapidly disseminating new research reports via this repository. Affiliated publications have also been added to the collection. As of 2025, the JTRP collection has over 4 million downloads, with some particularly popular reports having over 35,000 downloads.