TRANSPORTATION POOLED FUND PROGRAM
QUARTERLY PROGRESS REPORT

Date: _March 31, 2022_

Lead Agency (FHWA or State DOT): ______Indiana DOT_________________________________

INSTRUCTIONS:
Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the current status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.

Transportation Pooled Fund Program Project # *(i.e, SPR-2(XXX), SPR-3(XXX) or TPF-5(XXX)* ***TPF 5-387***		**Transportation Pooled Fund Program - Report Period:** X Quarter 1 (January 1 – March 31) ☐Quarter 2 (April 1 – June 30) ☐Quarter 3 (July 1 – September 30) ☐Quarter 4 (October 1 – December 31)
Project Title: **Development of an Integrated Unmanned Aerial Systems (UAS) Validation Center**		
Name of Project Manager(s): **Tommy E. Nantung**	**Phone Number:** **(765) 463-1521 ext. 248**	**E-Mail** tnantung@indot.in.gov
Lead Agency Project ID:	**Other Project ID (i.e., contract #):**	**Project Start Date:** 1/1/2019
Original Project End Date: **12/31/2022**	**Current Project End Date:** **12/31/2022**	**Number of Extensions:** None

Project schedule status:

☐On schedule ☐ On revised schedule ☐ Ahead of schedule X Behind schedule

Overall Project Statistics:

Total Project Budget	Total Cost to Date for Project	Percentage of Work Completed to Date**
$650,000	**$422,758**	**80%**

Quarterly Project Statistics:

Total Project Expenses and Percentage This Quarter	Total Amount of Funds Expended This Quarter	Total Percentage of Time Used to Date**
$23,066	**3.5%**	**93%**

**Since end date has been extended, project percentages have been updated (estimates)

Project Description:
This study proposes to develop the basic standards, protocols, and testing requirements that a given UAS must meet and demonstrate for a particular application.

Progress this quarter (includes meetings, work plan status, contract status, significant progress, etc.):

- The development of the UAS Evaluation Chamber for Bridge Inspection has been completed. As discussed in previous reports, the chamber presents a GPS denied environment that can be used to evaluate UAS in a controlled and repeatable environment. A scoring rubric for UAS is currently being developed. The draft standard, less the scoring rubric, is attached for review.
- A standardized "cold weather" evaluation test is completed. This test will be used to provide a relative indication of the effect of cold weather (in the range of 20F to 30F) as compared to "warm" weather (<60F) operation times of a UAV. A scoring rubric for UAS is currently being developed. The draft standard, less the scoring rubric, is attached for review.
- The development of a standardized "turbulence test" is well underway. This test will be used to evaluate the performance of the UAS in turbulent wind conditions to determine the effect of turbulence on the quality of the data collected.
- The Research Team has scheduled two UAV pilots who regularly inspect bridges to perform beta testing of the UAS Evaluation Chamber for Bridge Inspection test in the next quarter. More pilots will be scheduled in the next quarter.

Anticipated work next quarter:

- Bring various bridge inspectors to the S-BRITE center to get real-world feedback on the test. These data will be used to finalize the scoring and test procedures for evaluating the performance of UAS within the UAS Evaluation Chamber.
- Finalize the turbulence tests along with the pilot check list and scoring rubrics.
- Schedule Project Panel meeting for some time in the 2nd Quarter of 2022.

Significant Results:

Circumstance affecting project or budget. (Please describe any challenges encountered or anticipated that might affect the completion of the project within the time, scope and fiscal constraints set forth in the Agreement, along with recommended solutions to those problems).

1. The COVID-19 restrictions resulted in Purdue University shutting down entirely in Mid-march 2020. All access to laboratory facilities were halted effectively bringing all research to a standstill. In mid-June 2020, standard Operating Procedures were being developed for review by the University to begin safe operations. Bowen Laboratory and the S-BRITE Center were cleared to allow research to re-start in mid-July of 2020. Clearly, COVID has been a major impact on this and other research projects. The Research Team continues to try and work hard to try and make up for lost time due to the laboratory shut downs while still working as safely as possible and within the confines of Purdue's COVID-19 operation procedures.

Potential Implementation:
None to date

APPENDIX B

Standard Unmanned Aerial Systems Evaluation Chamber for Bridge Inspection

Table of Contents

1. Introduction

This appendix provides mandatory requirements when evaluating any Unmanned Aerial System capabilities and performance in bridge inspection using a controlled environment known as Evaluation Chamber.

2. Scope

2.1 The procedures and standards outlined in this document govern any Unmanned Aerial System (UAS) intended for use in bridge inspection.

2.2 The Unmanned Aerial Vehicle (UAV) must fall under the category 'small' defined in the Code of Federal Regulations (14 C.F.R.§107.3). The CFR define a small UAV as weighing less than 55 pounds (on takeoff).

2.3 The Unmanned Aerial Vehicle (UAV) must have a propeller-tip-to-propeller-tip distance less than or equal to 2.5 feet to comply with minimum clearance distance during the test.

2.4 UAVs with a propeller-tip-to-propeller-tip distance greater than 2.5 feet but less than or equal to 3 feet 4 inches can be tested under this document. For this case, it may be prudent to ensure the UAV has some protective equipment that inhibits the impact of proximity effects in the vehicle when flying (e.g., protective cage, propeller guards, etc.) to protect the propellers from damage as well as the safety of the pilot.

2.5 The test method does not provide any guidance regarding the assessment of camera resolution or other forms of imaging sensors or devices attached to a UAV.

2.6 The overall test is conducted within a controlled environment referred in this document as 'evaluation chamber'.

2.7 This test method is one of the several tests to evaluate overall system capabilities for the inspection of bridges using UAVs.

2.8 The U.S. Customary Units (a.k.a. Imperial Units) are used throughout this document.

3. Definitions

3.1 Unmanned Aerial System: or Unmanned Aircraft System (UAS), is a system capable of flying under the control of a person who is not present in the vehicle itself. A UAS includes the vehicle, the vehicle's pilot, sensors, and additional features.

3.2 Unmanned Aerial Vehicle: (UAV) or drone are aircraft remotely controlled by a computer, a navigator on the ground or a combination of both, and do not require a pilot to be physically present on the vehicle when flying.

3.3 Pilot/Inspector: is the human element in the system. The pilot in command is responsible for controlling the UAV to fly and perform different tasks during takeoff, landing, and throughout the mission. The inspector is the individual deciding where to fly, what to focus on and the data interpretation. The pilot may also supervise the vehicle while under the control of an autonomous flight software. The pilot and inspector may be the same individual, but this is not required.

3.4 Propeller-tip-to-propeller-tip distance: distance between the exterior tip of one propeller and the exterior tip of the opposite propeller, or the element in the UAV located at the farthest from the center of the vehicle in the horizontal plane (rotor, spherical shell, propeller guards, etc.).

In most cases this distance can be easily found by pointing two opposite propellers towards each other and measuring the distance between the exterior tips, as presented in Figure 1.

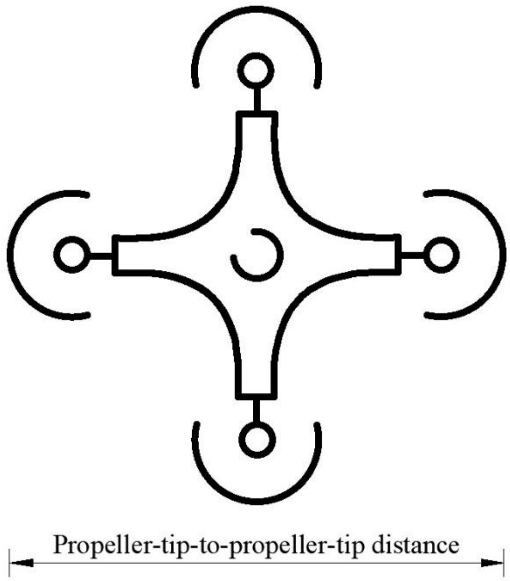


Figure 1 Illustration of propeller-tip-to-propeller-tip distance in a UAV.

3.5 Evaluation chamber: the testing scenario and environment described in this document is referred for brevity as the 'evaluation chamber'.

3.6 Small Unmanned Aerial Systems: according to the Code of Federal Regulations, 14 C.F.R.§107.3, a small UAV is a vehicle that weighs less than 55 pounds on takeoff.

3.7 Proximity effects: drift and changes in quasi-stationary state of the UAV when hovering or flying caused by its proximity to elements above, below or next to the UAV.

3.8 Protective cage: a surrounding element, sometimes spherical, attached to the UAV to protect it from impact to nearby objects.

3.9 Global Navigation Satellite System (GNSS): is a satellite system that provides information of location to a receiver on Earth and part of it is the Global Positioning System (GPS). In this document, the term GPS refers to the GNSS most prevalent and commonly used in the US.

3.10 Visual Observer: according to the Code of Federal Regulations, 14 C.F.R.§107.3, a visual observer is a person designated by the pilot in command to assist the pilot in command or the person manipulating the controls of the UAS to see and avoid air traffic or objects on the path of the UAS.

4. Significance and Use

4.1 This performance test method is part of a comprehensive set of tests applied to UAS by the UAS Validation Center to provide information and compliance of the system before inspecting structures, particularly bridges.

4.2 This test method was developed to be easily replicated, fabricated, and inexpensive. In addition, since the test is standardized, comparing results between different testing locations is possible.

4.3 This test method does not include the grading criteria for the UAS who completes the test. The grading criteria can be found in the test method: Grading Criteria for the Unmanned Aerial Systems Evaluation Chamber for Bridge Inspection.

5. Summary of Test Method

5.1 This test method is intended for small Unmanned Aerial Systems (UAS) that comply with weight and horizontal dimension limitations presented in the scope of this document. This test method specifies the steps to follow for a given UAS to collect information and maneuver inside a chamber representing general shapes of common elements found in bridge structures. This test method allows the assessment of a given UAS under conditions found in bridges and other structures to qualify its performance when the same conditions are encountered in the field. This test method is conducted in an environment with no GPS signal (GPS-denied environment).

5.2 The maneuvering tasks require the UAS to enter a 40-feet steel cargo container to assess the status of elements placed inside and report any defect or other information deemed as required data in the test. The UAS will need to maneuver to reach all the elements from all sides, change the camera direction, fly inside the elements, and provide different visual angles to the elements from different locations. In addition, these tasks require the UAS to maneuver accounting proximity effects and clearance distance along the test to guarantee the integrity and complete collection of all the defects in the evaluation chamber.

6. Apparatus

6.1 Test Environment:

6.1.1 This test method is conducted inside a standard steel 40-feet cargo container or environment with similar proportions and interior operational characteristics. The external dimensions of the container are detailed below and in Figure 2.

- 40 feet of length,
- 8 feet of width,
- and 8 feet 6 inches of height.

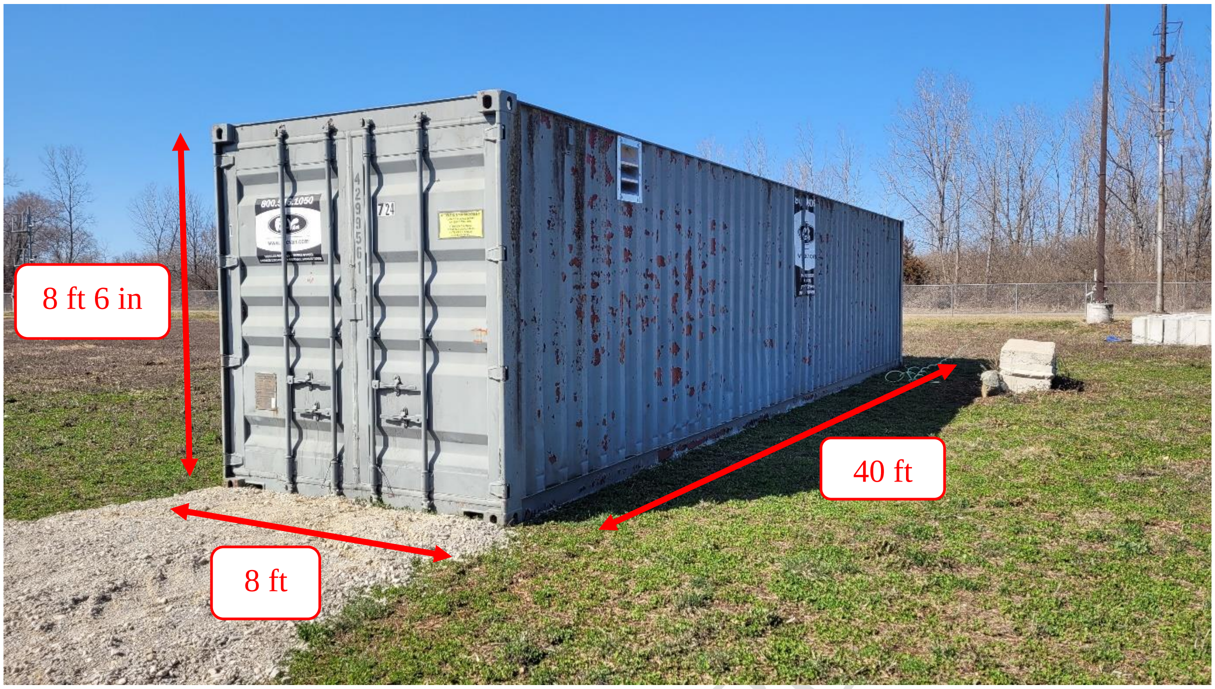


Figure 2 Container where the proposed evaluation chamber test takes place.

6.1.2 The space will contain supplementary lights provided in locations where natural light does not provide enough visibility inside the evaluation chamber. Location and details are provided in the following sections.

6.1.3 The cargo container provides an environment for this test with limited access to GPS signal, controlled lighting, and shielding from wind, precipitation, and sudden changes in temperature. This standard allows repeatability of the evaluation of UAS independent of outdoor conditions and location.

6.2 Test Site:

6.2.1 The test site where the cargo container is located must be level within three (3) inches in the 40-foot dimension and one (1) inch in the 8-foot dimension.

6.2.2 The test site must provide a power source nearby to allow the operation of the interior lighting.

6.2.3 Lighting shall be placed at the top end of one of the walls of the container as shown in Figure 6. The lights shall provide a color rendering index (CRI) of at least 80 with a length of 44 inches, and 5500 Lumen. LED light is recommended.

6.3 Evaluation Chamber:

6.3.1 The evaluation chamber includes “real” *steel specimens* (identified with the letter S followed by a number, e.g.: S1, S2, S3, etc.), “real” *concrete specimens* (identified with the letter C followed by a number, e.g.: C1), and *components* intended to simulate various geometric configurations on which other features are mounted (identified with numbers, e.g.: 1, 2, 3, 4, 5, 6, 7).

6.3.2 An isometric view of the evaluation chamber is presented in Figure 3 to illustrate the location of the elements. A detailed labeling of all the elements inside the evaluation chamber follows in Figure 4 and Figure 5. The dimensions and distances between elements are detailed next to each element in Figure 6 and Figure 7.

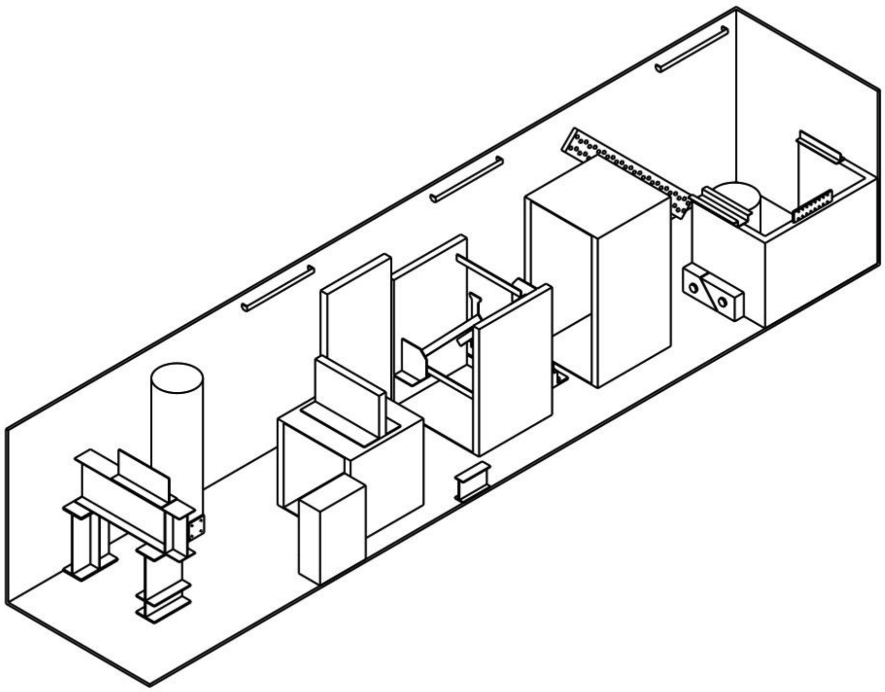


Figure 3 General isometric view of elements inside the evaluation chamber.

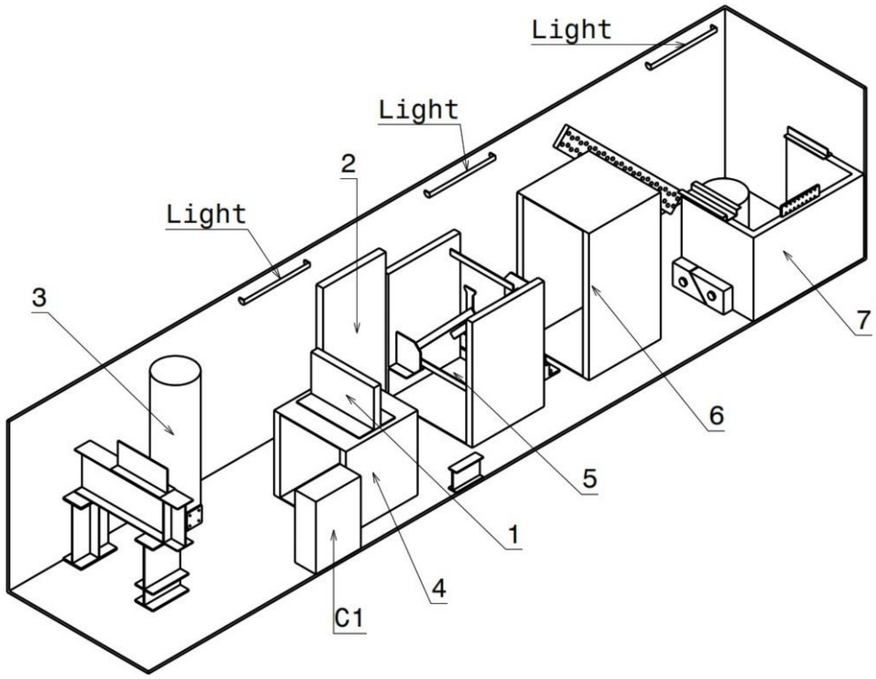


Figure 4 General isometric view with labels of components, concrete elements, and lights inside the evaluation chamber.

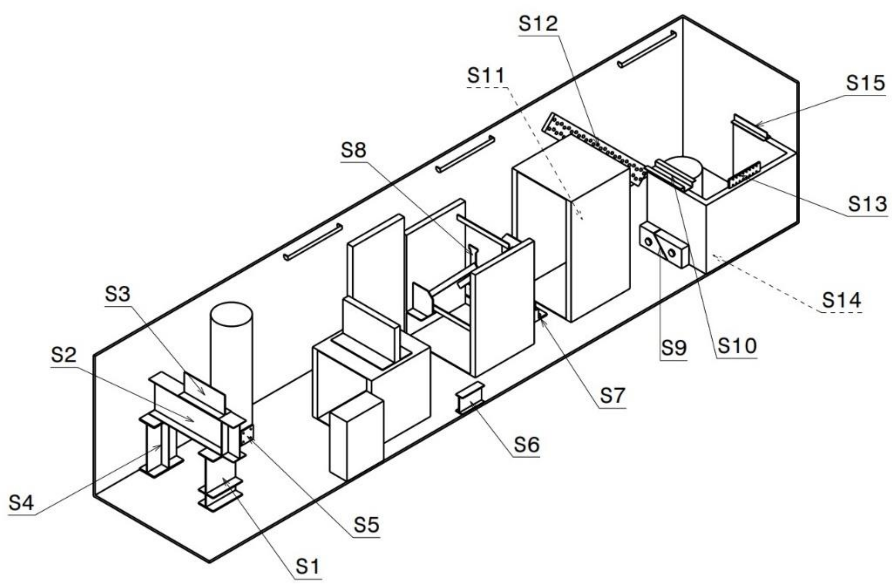


Figure 5 General isometric view of steel elements inside the evaluation chamber.

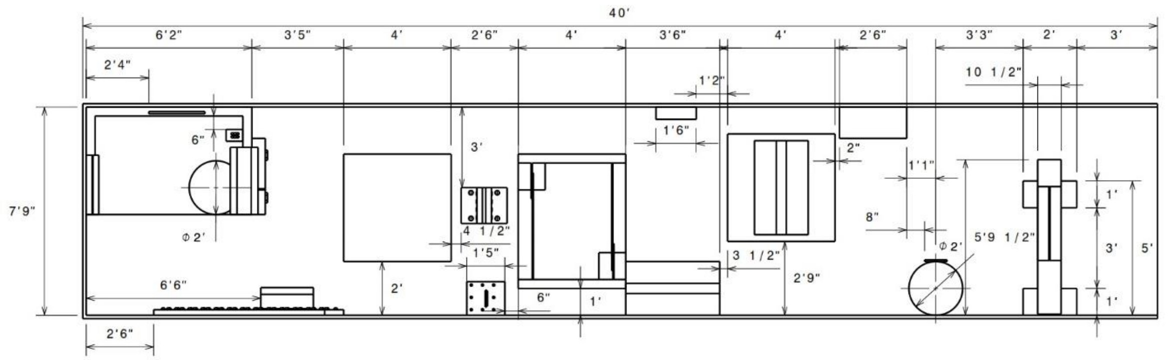


Figure 6 General top view of the evaluation chamber with clearance distance and dimension of elements.

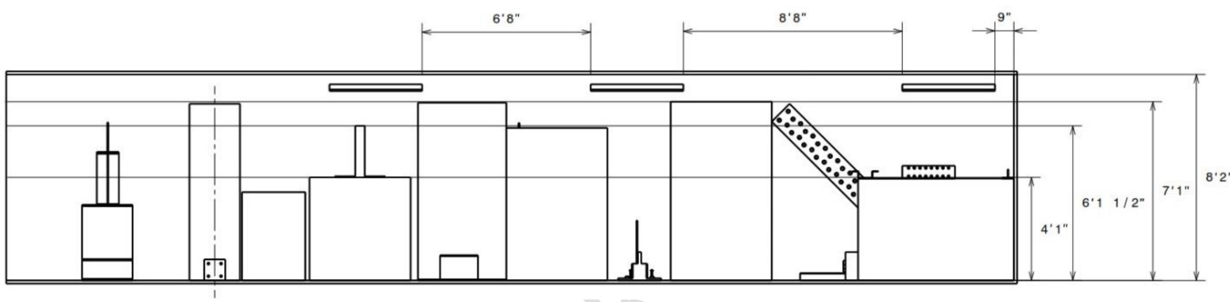


Figure 7 General elevation view of the evaluation chamber including the horizontal location of the lights.

6.4 General guidelines for elements inside the evaluation chamber

6.4.1 The evaluation chamber contains objects that resemble components of bridge structures to be inspected using UAS that allow for repeatable testing. Therefore, the elements inside the evaluation chamber will be referred to in the following section as components.

6.4.2 The name of each element inside the evaluation chamber follows the name provided in Figure 3, Figure 4, and Figure 5. The components inside the chamber have been identified with a label with the dimensions presented in Figure 8.

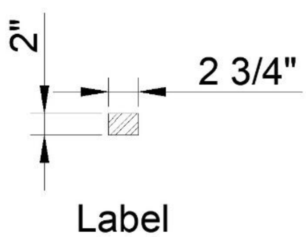


Figure 8 Label identifying components inside the evaluation chamber.

6.4.3 Some components inside the evaluation chamber present defects directly in their concrete or steel surfaces, such as cracks, delamination, spalling, corrosion, etc.

6.4.4 Other components shall have smooth surfaces to place images of concrete and steel defects in their faces and therefore the use of plywood, lumbers, and sonotube for the construction of these components is suggested.

6.4.5 The exact location of the images in the faces of the component is illustrated in the following sections. A rectangle with a number with 4 digits has been used to identify an image of an image as presented in Figure 9. The numbers inside each image correspond to the name of the image in Appendix A which includes an inventory of 120 images of high-quality defects.

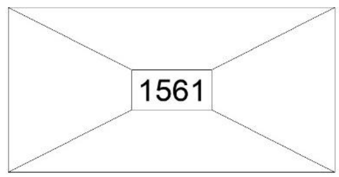


Figure 9 Illustration of an image of an image with a 4-digit identifier.

6.4.6 The images of high-quality defects in steel and concrete structures are presented in Appendix A of this document along with a detailed explanation of each defect. The second digit from the left has been used to identify the type of material illustrated in the image: 5 for concrete and 7 for steel. Appendix A includes 120 images of steel and concrete members containing defects such as corrosion, cracks, spalling, delamination, staining in concrete, defects in welds, etc.

6.4.7 Images in Appendix A are interchangeable between others with the same material. An image of concrete (second digit 5) shall be replaced with another image of concrete. The same concept is applied for images of steel.

6.4.8 The images in Appendix A or any image to be used in the evaluation chamber must meet the minimum requirements presented in the report "Camera Settings & Image Evaluation for UAS–Based Infrastructure Monitoring" and the following guidelines:

6.4.8.1 The images shall be printed in a white non-glossy paper. Papers heavier than normal paper are recommended (i.e., paper weight > 20 lb. / 75 gsm).

6.4.8.2 The images shall be printed in the size and resolution detailed for each component. The images in Appendix A contain a measuring tape next to the steel or concrete element to aid with the correct sizing (i.e., printing in full size 1:1).

6.4.8.3 For the use of any image not included in Appendix A, the image must comply with the same guidelines described before and contain an element with known size (e.g., a measuring tape) to scale the whole image using computer technologies. The printing setting shall be in full size (1:1). The dimension of the image when printed in full size has been presented in Appendix A

6.4.8.4 Images in Appendix A contain a general description that a new image shall comply before replacing an existing one from Appendix A.

6.4.8.5 The highest resolution available has already been set for each image file in Appendix A (>300 PPI, i.e., 300 pixels per inch or higher when possible) and no modification in resolution shall be performed..

6.4.8.6 When printing, the document dimension for each image shall be set according to the dimensions presented per each file in inches. The printer shall be set to achieve the highest DPI (dots per inch) available, e.g., 300 DPI.

6.4.9 As a final verification of the quality of the images obtained inside the evaluation chamber, three resolution charts were located in the original images and as a result appeared in the images printed and placed inside the evaluation chamber. The resolution charts used are: 2008 Bob Arkings Resolution Chart, ISO 12233 Resolution Chart, and EIA Resolution Chart 1956.

6.4.10 Three copies of DGK Color Tools High Resolution Chart 8.5x11" are placed in the faces of some components of the evaluation chamber. A rectangular representation with a hatched pattern has been used in the following sections to identify a resolution chart as presented in Figure 10. The developer of each resolution chart provides techniques to evaluate the capability of an image containing a resolution chart, and they are not covered in this document.

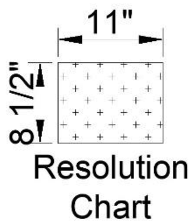


Figure 10 Resolution chart representation inside the evaluation chamber.

6.4.11 In the following sections, each element inside the evaluation chamber is described in detail. If the element is classified as a component (i.e., elements resembling geometric configurations of structures), a location of the images to be placed in the faces of that component is presented. Areas where images are not possible to locate due to elements surrounding the component have been identified with a dashed line. A hatch pattern has been used to illustrate faces in isometric views where only a part of the face is used to place images.

6.4.12 The faces where the images shall be located have been labeled in numerical order (1, 2, 3, 4, etc.) in clockwise rotation for each component following the order: top face, right face, bottom face, left face, front face, and back face. Top face is the one closest to the ceiling, bottom face is the one closest to the floor, and front face is the one closest to the entrance of the container. If one of them is missing, the order continues with the next face.

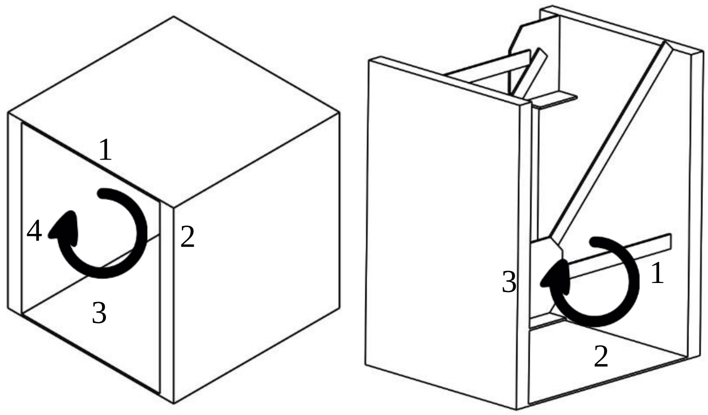


Figure 11 Illustration of numerical order followed to label the faces in components inside the evaluation chamber

6.4.13 The following example is used to illustrate the name of the faces: if a clock is located in the vertical plane at the door of the cargo container facing outdoors, top face corresponds to 12, right face to 3, bottom face to 6, left face to 9, the front face is facing the entrance of the container, and the back face is facing indoors. The entrance of the container is located on the left side of Figure 4.

6.4.14 To provide a further quality assessment with "real" structures, several steel and concrete elements with known defects were introduced to the evaluation chamber and placed with the components as presented in Figure 3.

6.4.15 The evaluation chamber shall include similar steel and concrete elements to the elements made of steel and concrete described in the following section (e.g., elements S1 to S14, and C1). The similarity is achieved in terms of size and purpose. In terms of size, the elements shall fit in the areas designated for the steel and concrete elements placed in the evaluation chamber but always comply with the clearance distance used to design the components. In terms of purpose, the elements shall comply with the goal of the element inside the evaluation chamber as described in each element. They shall also cover steel and concrete defects well-known and documented by the testing facility.

6.5 Elements inside the evaluation chamber

6.5.1 Component 1

6.5.1.1 Component 1 (Figure 12) is intended to evaluate the UAV response when approaching elements from above, such as during an inspection of a deck, when approaching elements with vertical surfaces, and during inspection of smaller more confined spaces.

6.5.1.2 The dimensions of Component 1 are presented in Figure 12:

- Width: 3 feet 6 inches.
- Height: 2 feet.
- Depth: 4.5 inches.

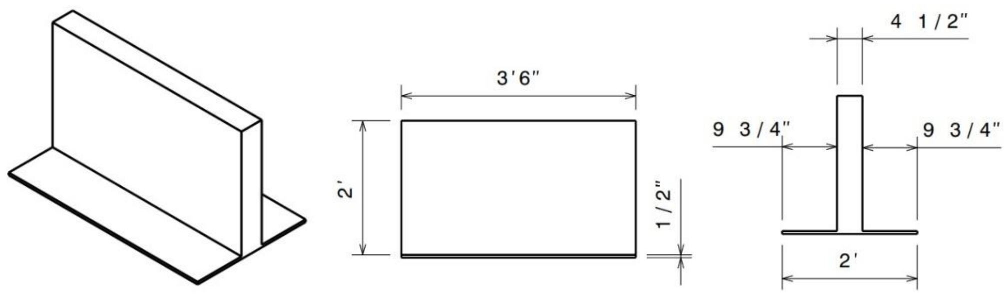


Figure 12 Isometric view, front view, and side view of Component 1.

6.5.1.3 The faces in this component where images from Appendix A shall be located are detailed in Figure 13 and Figure 14.

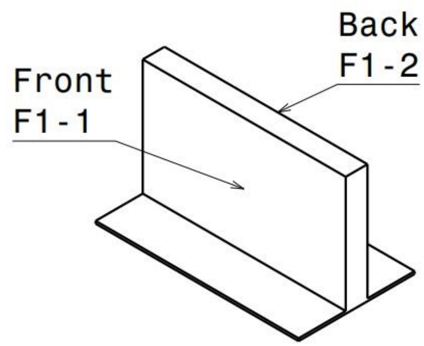


Figure 13 Faces of Component 1

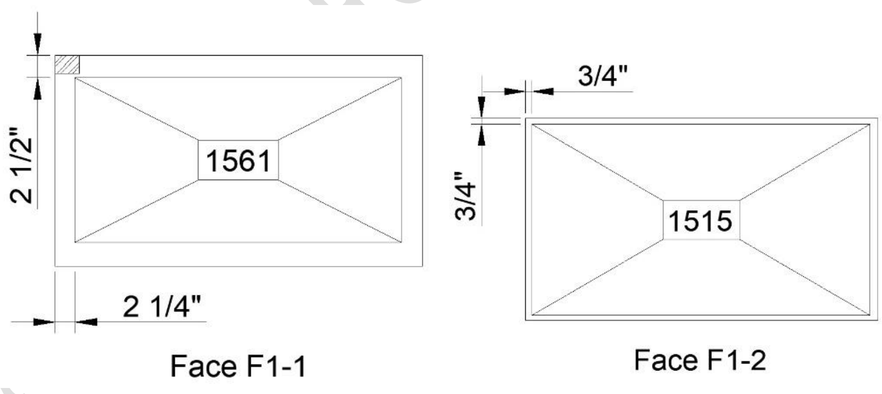


Figure 14 Images of images in faces of Component 1

6.5.2 Component 2

6.5.2.1 Component 2 (Figure 15) portrays tall and slender faces in bridge elements such as piers, walls, girders, and other vertical planes in open environments. The component is high enough to test both ground and ceiling effect, and provide two tall faces where defects will be located.

6.5.2.2 The dimensions of Component 2 are presented in Figure 15:

- Width: 3 feet 6 inches.

- Height: 7 feet.
- Depth: 4.5 inches.

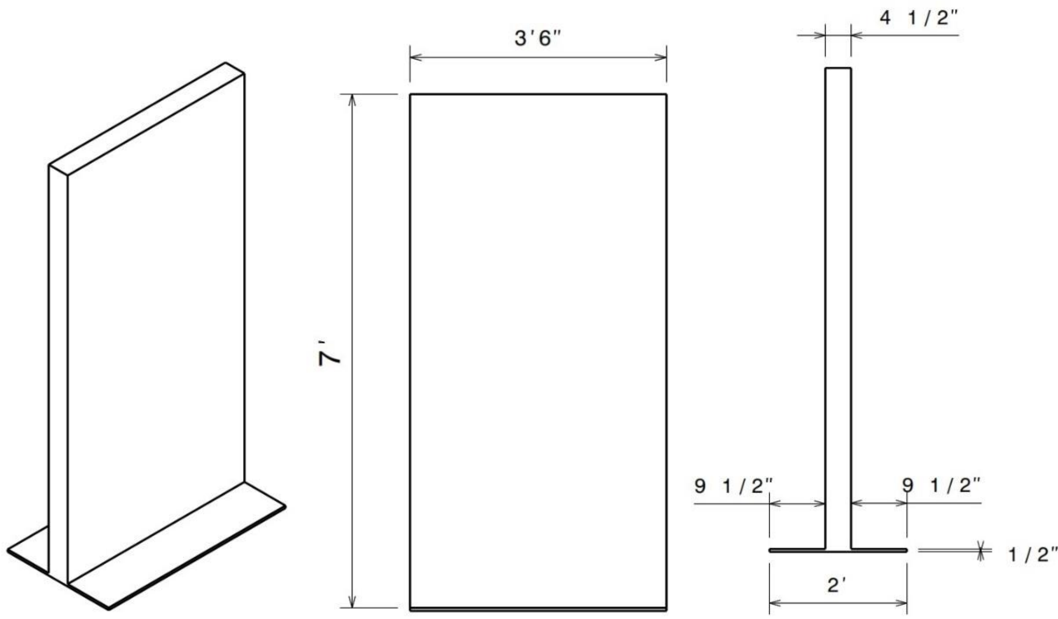


Figure 15 Isometric view, front view, and side view of Component 2.

6.5.2.3 The faces in this component where images from Appendix A shall be located are detailed in Figure 16 and Figure 17.

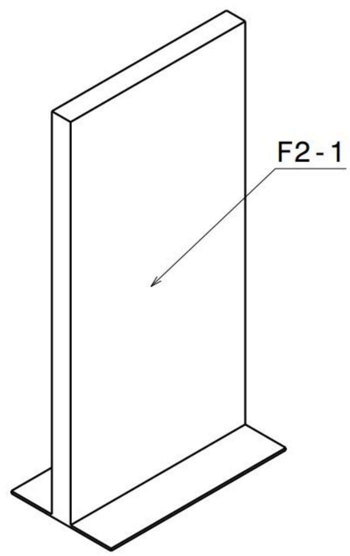


Figure 16 Faces of Component 2

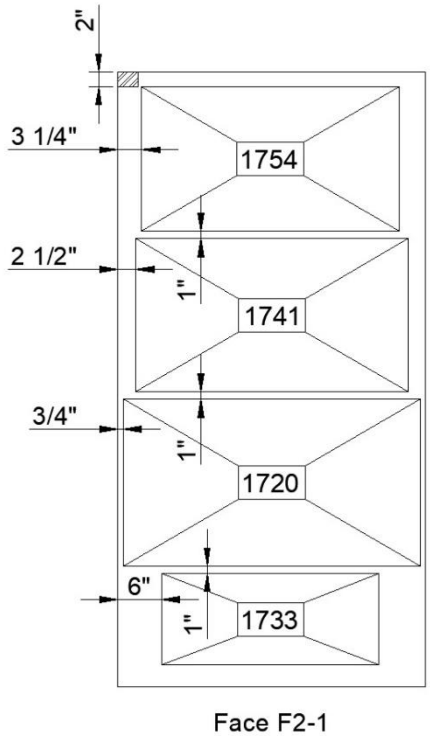


Figure 17 Images of images in face of Component 2

6.5.3 Component 3

6.5.3.1 Component 3 (Figure 18) portrays the shape, slenderness, and height of cylindrical components with round surfaces where the shape will force the UAV to take different images of the same area to provide a complete assessment of the element in the horizontal and vertical direction. The component shall be located to avoid the access of the UAV to the entire face (avoiding a 360° assessment), instead the component must be placed against a wall of the container achieving that some areas will be hidden and difficult to reach by the UAS.

6.5.3.2 The dimensions of Component 3 are presented in Figure 18:

- Diameter: 2 feet.
- Height: 7 feet.

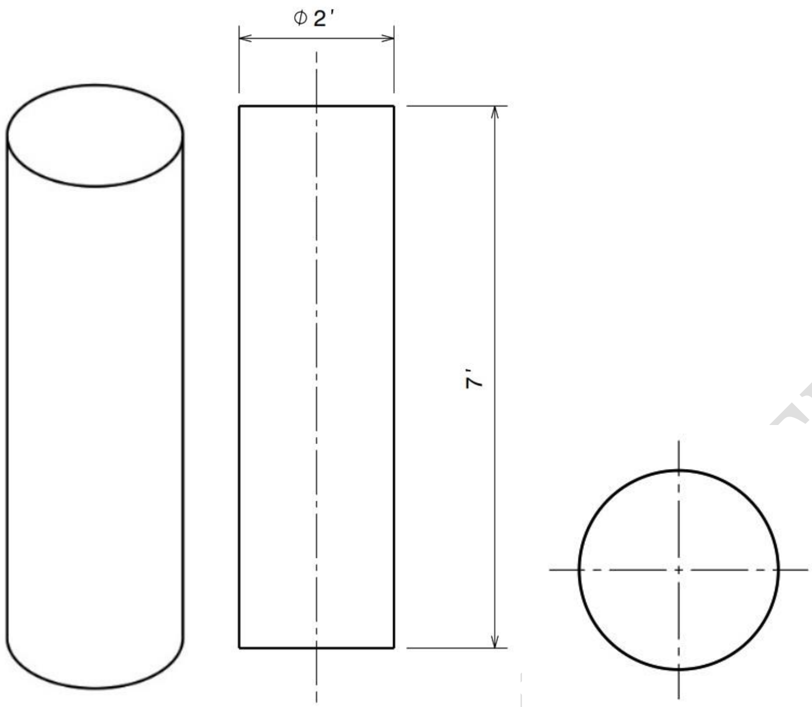


Figure 18 Isometric view, front view, and top view of Component 3.

6.5.3.3 The faces in this component where images from Appendix A shall be located are detailed in Figure 19 and Figure 20.

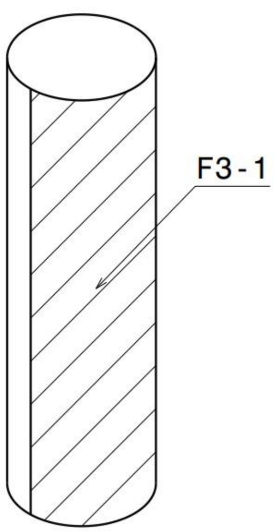


Figure 19 Faces of Component 3

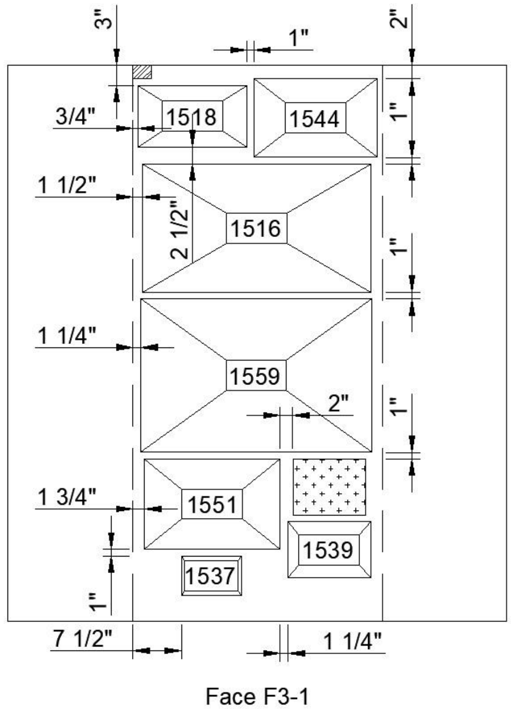


Figure 20 Images of images in face of Component 3

6.5.4 Component 4

6.5.4.1 Component 4 (Figure 21) evaluates cases where UAS must view the object of interest from below (i.e., looking up). Component 4 also represents a passage within a confined space, such as inside a box girder.

6.5.4.2 The dimensions of Component 4 are presented in Figure 21:

- Internal width: 3 feet 4 inches.
- External width: 4 feet.
- Height: 4 feet.
- Depth: 4 feet.

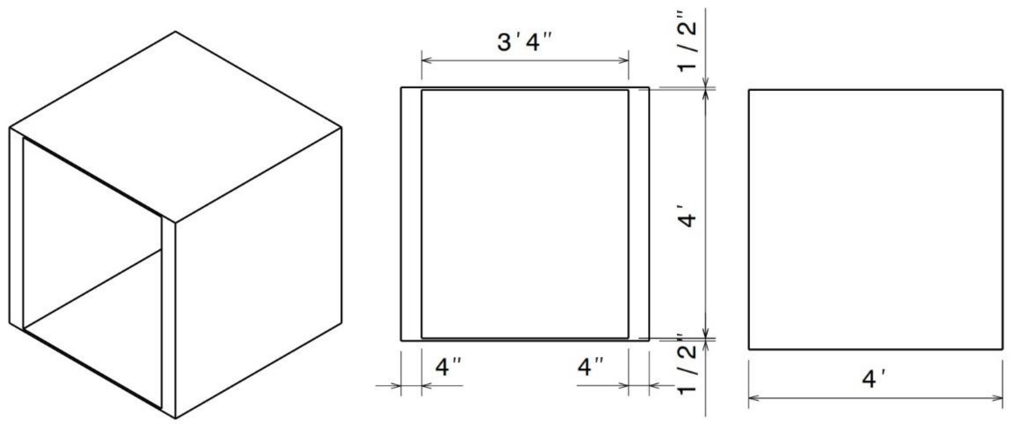


Figure 21 Isometric view, front view, and side view of Component 4.

6.5.4.3 The faces in this component where images from Appendix A shall be located are detailed in Figure 22 and Figure 23.

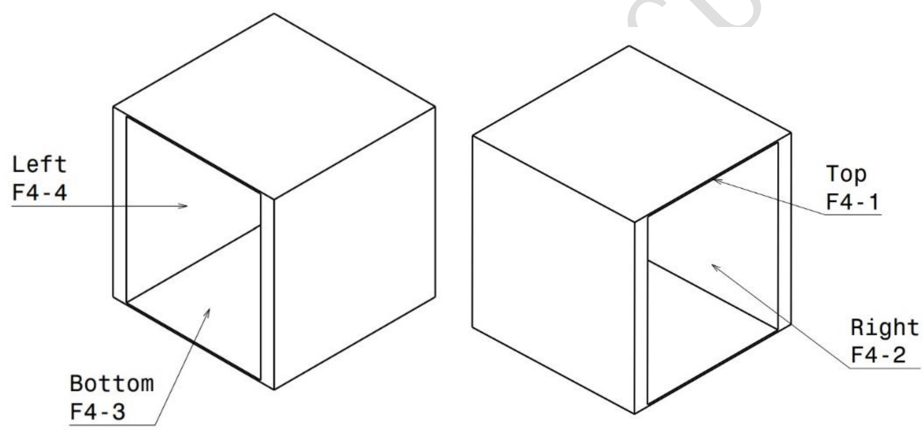


Figure 22 Faces of Component 1

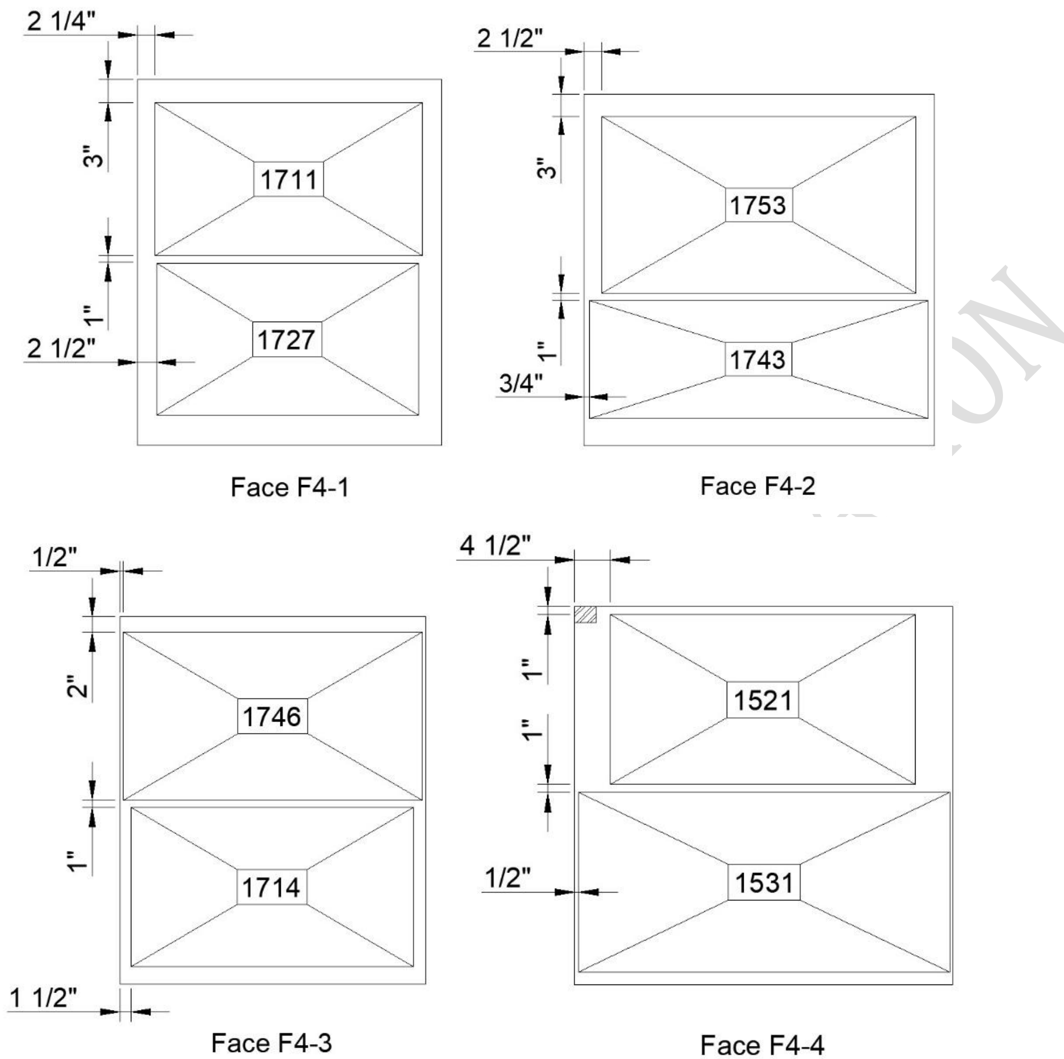


Figure 23 Images of images in faces of Component 4

6.5.5 Component 5

6.5.5.1 Component 5 (Figure 24 and Figure 25) represents cross frames and bracing elements. This component will be used to evaluate the UAS to fly across and inside thin and long elements, K frames, and truss elements in bridges.

6.5.5.2 The dimensions of Component 5 are presented in Figure 24 and Figure 25:

- Internal width: 4 feet 4 inches.
- External width: 5 feet.
- Height: 6 feet.
- Depth: 4 feet.
- Gusset plate bottom base: 12 inches by 12 inches.
- Gusset plate top and bottom length: 12 inches.

- Gusset plate middle length: 16 inches.
- Gusset plate height: 18 inches.

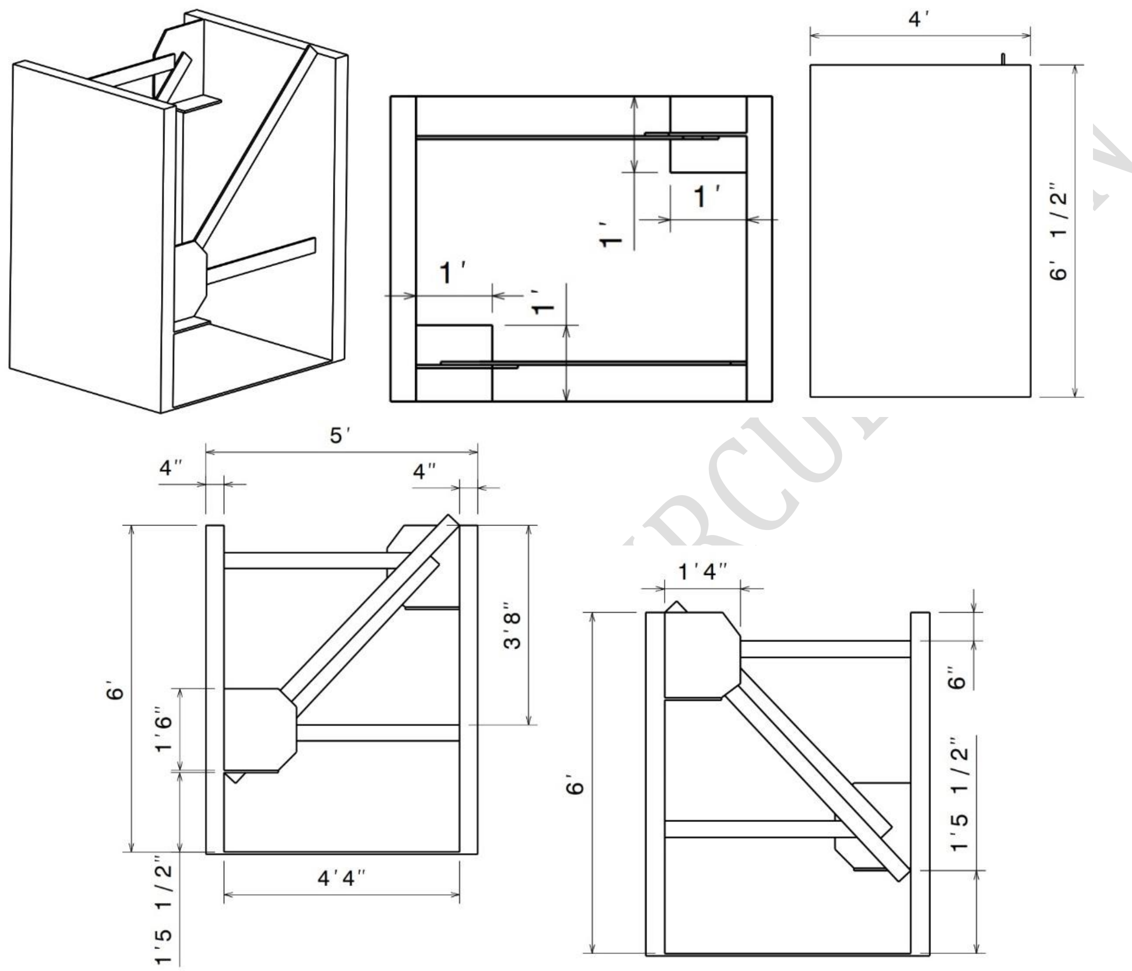


Figure 24 Isometric view, top view, side view, front view, and back view of Component 5

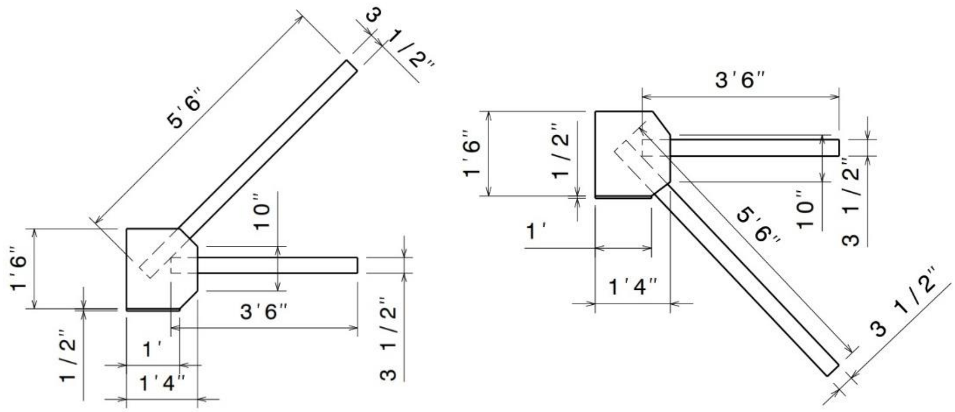


Figure 25 Details of parts of Component 5

6.5.5.3 The faces in this component where images from Appendix A shall be located are detailed in Figure 26 and Figure 27.

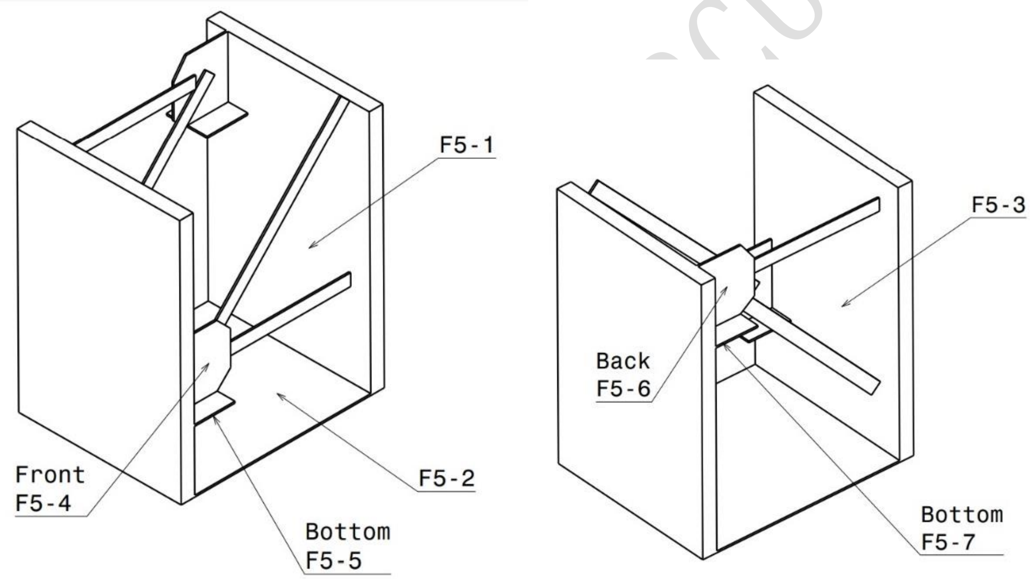
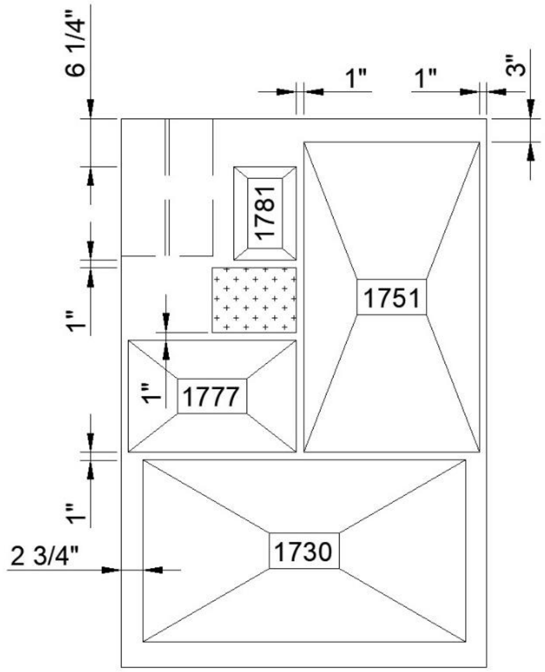
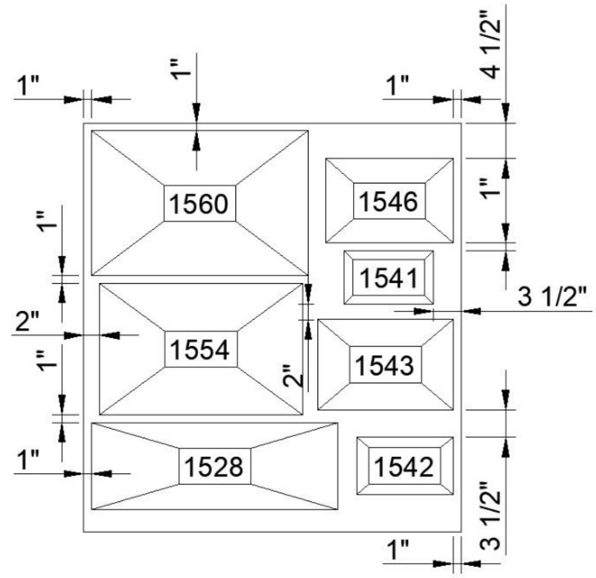


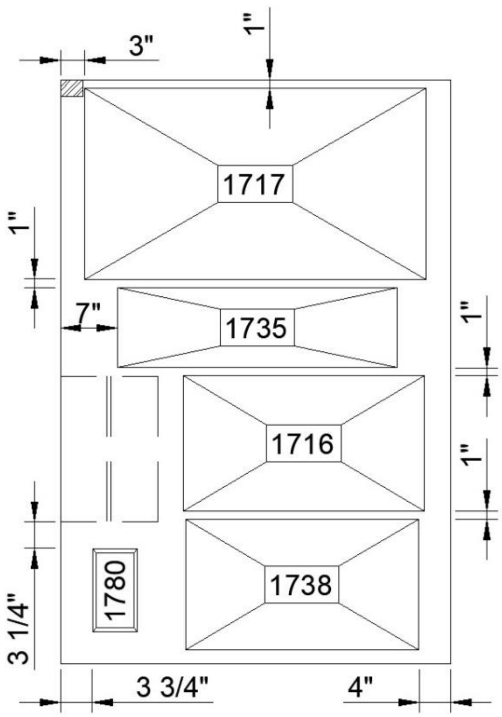
Figure 26 Faces of Component 5



Face F5-1



Face F5-2



Face F5-3

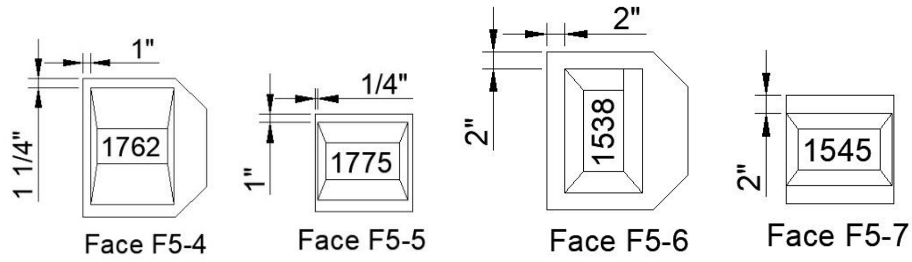


Figure 27 Images of images in faces of Component 5

6.5.6 Component 6

6.5.6.1 Component 6 (in Figure 28) portrays box structures, tight spaces with a combination of tall and slender structures, and locations underneath bridge structures with vertical faces. It provides an evaluation of cases where UAS must view the object of interest from below (i.e., looking up) and to explore both ground and ceiling effects in the same element.

6.5.6.2 The dimensions of Component 6 are presented in Figure 28:

- Internal width: 3 feet 4 inches.
- External width: 4 feet.
- Height: 7 feet.
- Depth: 4 feet.

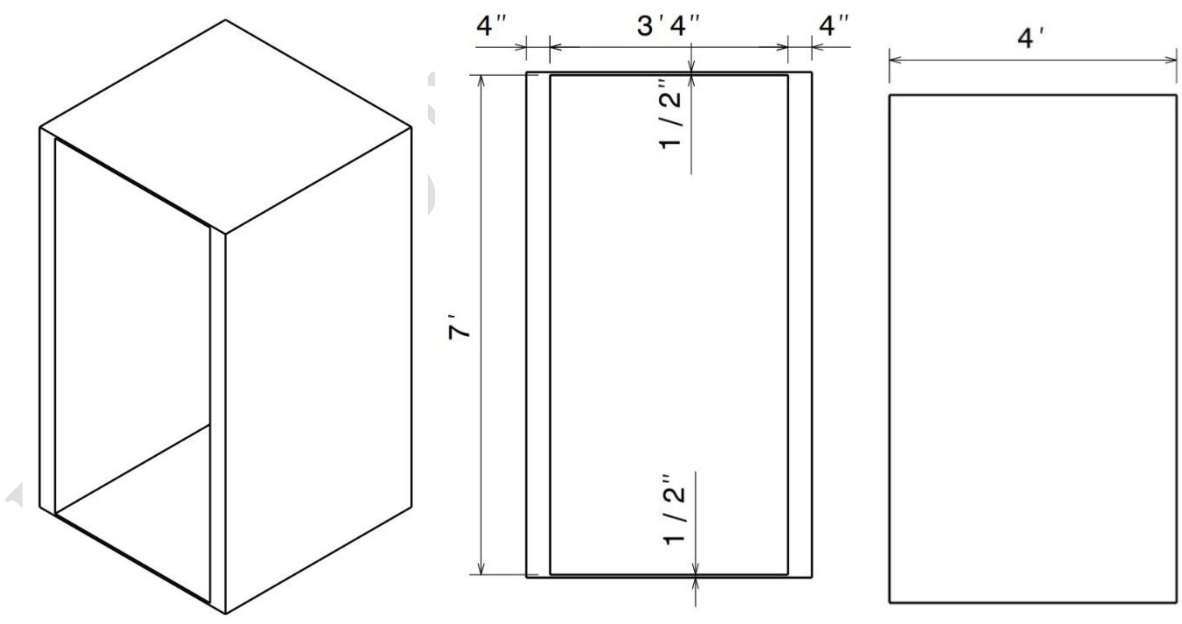


Figure 28 Isometric view, front view, and side view of Component 6

6.5.6.3 The faces in this component where images from Appendix A shall be located are detailed in Figure 29 and Figure 30.

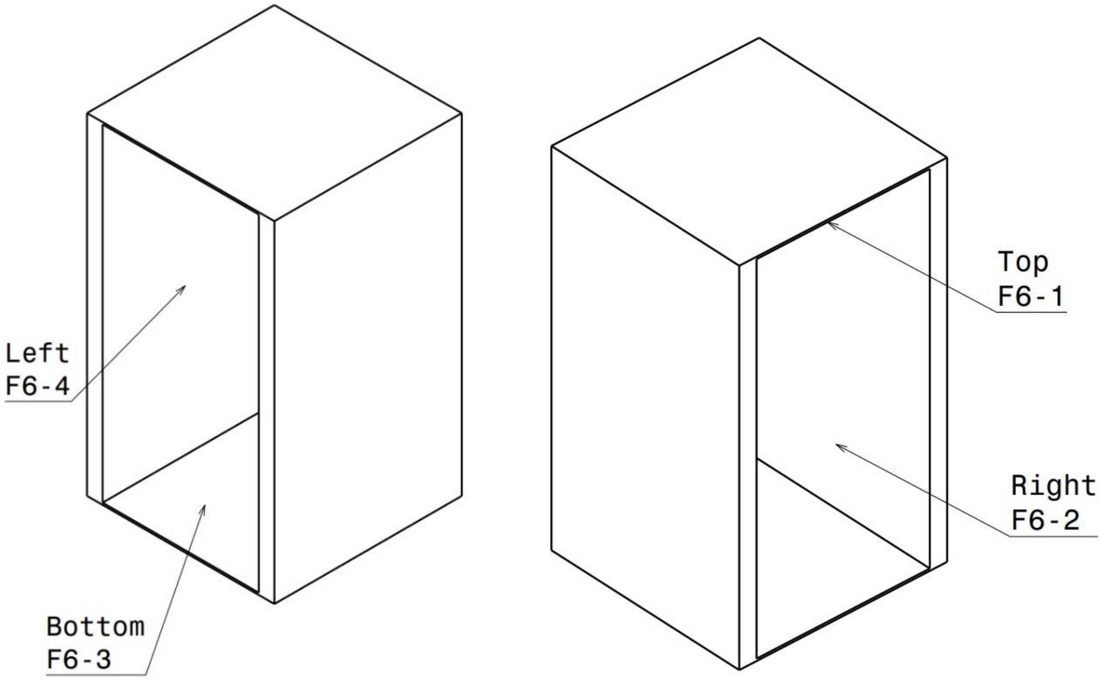


Figure 29 Faces of Component 6

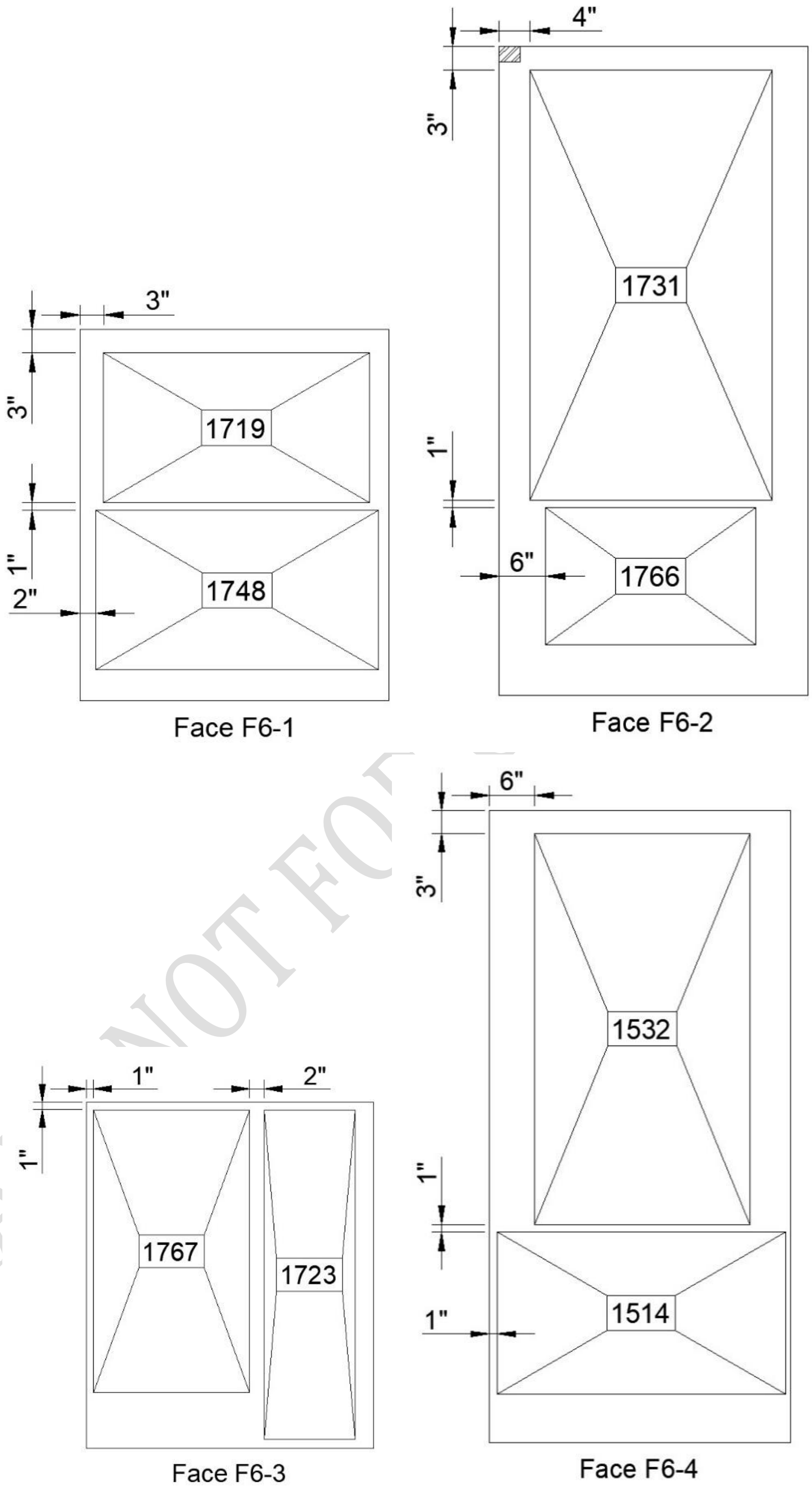


Figure 30 Images of images in faces of Component 6

6.5.7 Component 7

6.5.7.1 Component 7 (Figure 31) represents an element in which direct line-of-sight is almost completely inhibited. Additionally, Component 7 considers situations where the pilot has no visual line of sight from the ground, inspection in tight spaces, and round surfaces that would increase the difficulty of navigation inside the component. Additional enclosed and tight spaces in abutments, piers, and decks are considered.

6.5.7.2 The dimensions of Component 7 are presented in Figure 31:

- Internal width: 5 feet 6 inches.
- External width: 6 feet 2 inches.
- Height: 4 feet.
- Depth: 5 feet 6 inches.
- Diameter of the circular element: 2 feet.
- Height of the circular element: 4 feet (it will vary depending on the base, but the goal is to reach the same level of the overall component).

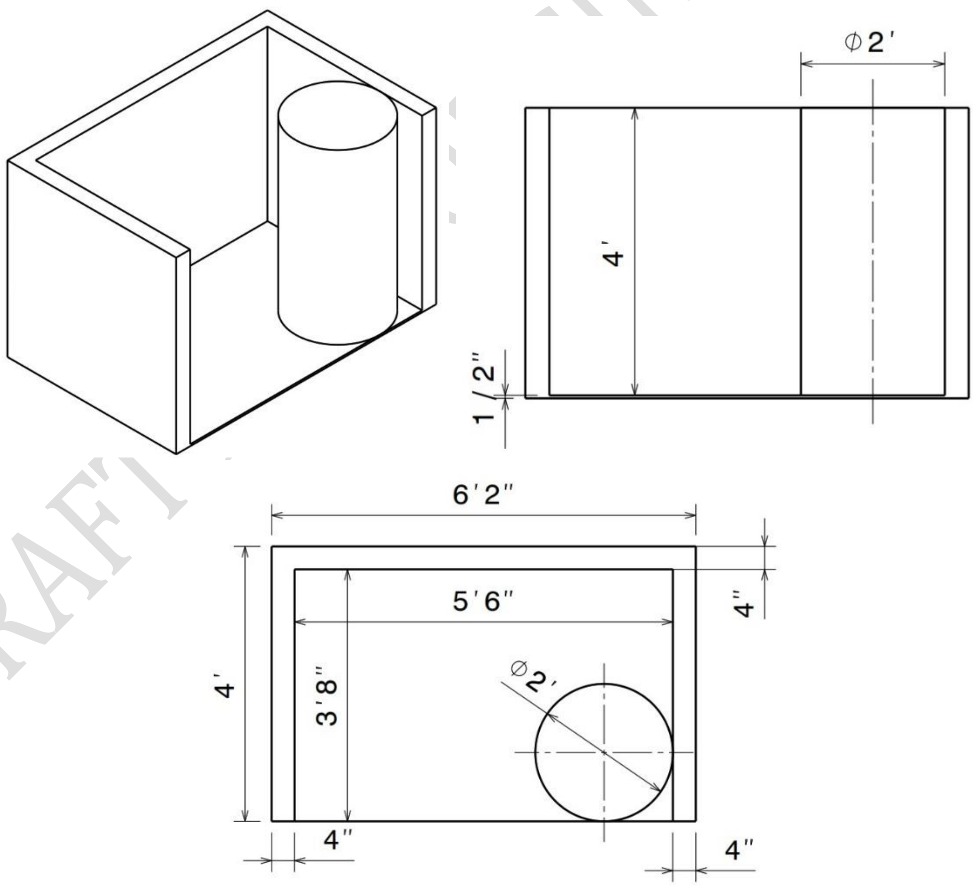


Figure 31 Isometric view, front view, and top view of Component 7

6.5.7.3 The faces in this component where images from Appendix A shall be located are detailed in Figure 32 and Figure 33.

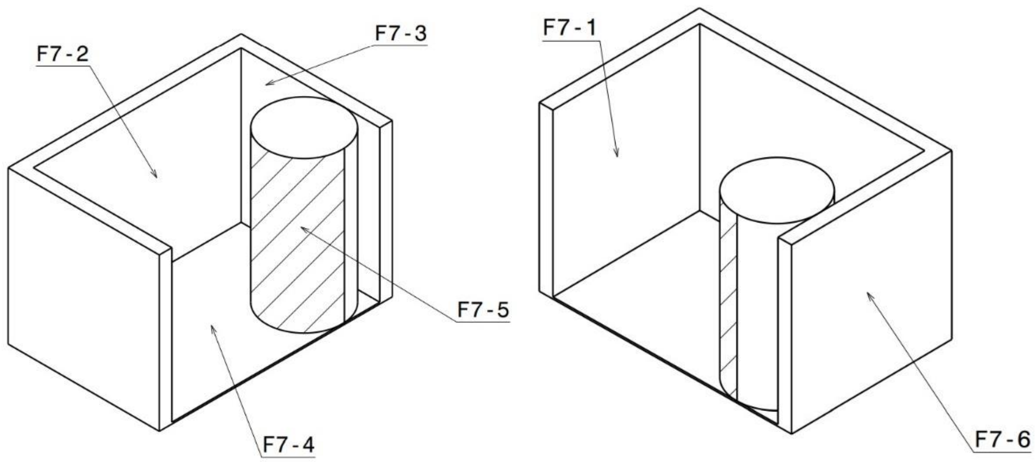


Figure 32 Faces of Component 7

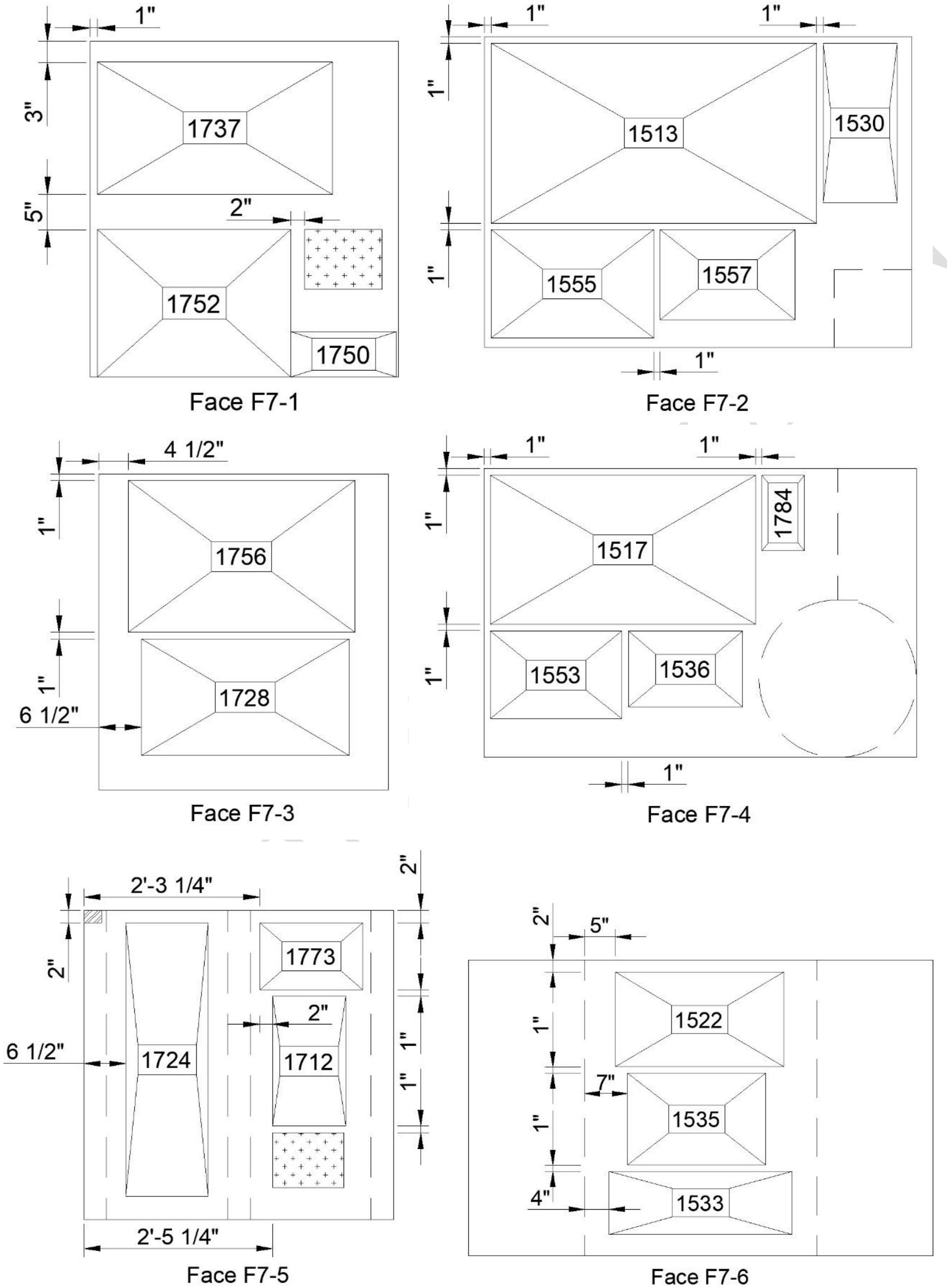


Figure 33 Images of images in faces of Component 7

6.5.8 Element S1

6.5.8.1 Element S1 (Figure 34) is a steel wide-flange beam with longitudinal stiffeners. The location allows inspection in areas between floor beams in tight spaces, welds, and hidden cracks in beams.

6.5.8.2 Defects addressed with this element shall include cracks and corrosion.

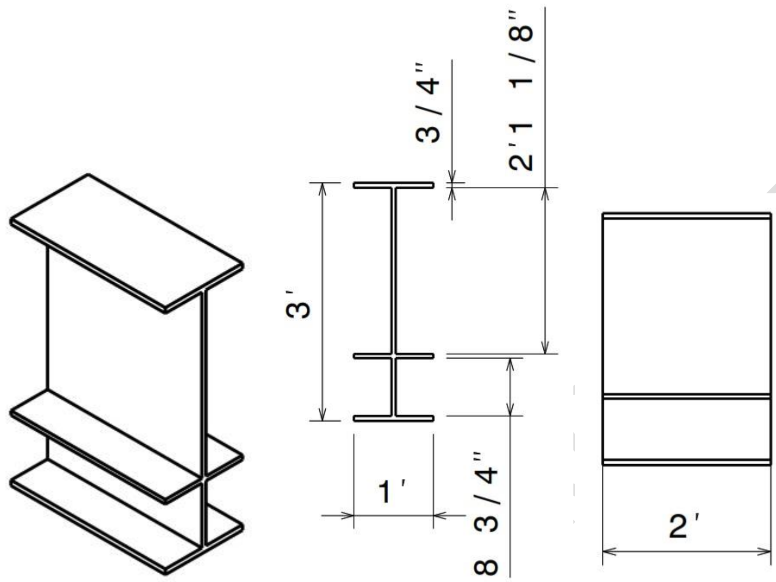


Figure 34 Isometric view, side view, and front view of element S1

6.5.9 Element S2

6.5.9.1 Element S2 (Figure 35) is a steel beam with longitudinal and transversal stiffeners. The location allows inspection in longitudinal areas of the web, the flanges, and stiffeners. In addition, one side of the web forces the camera of the UAV to work under overexposed scenarios.

6.5.9.2 Defects addressed in this element shall include corrosion and deformations caused by impact.

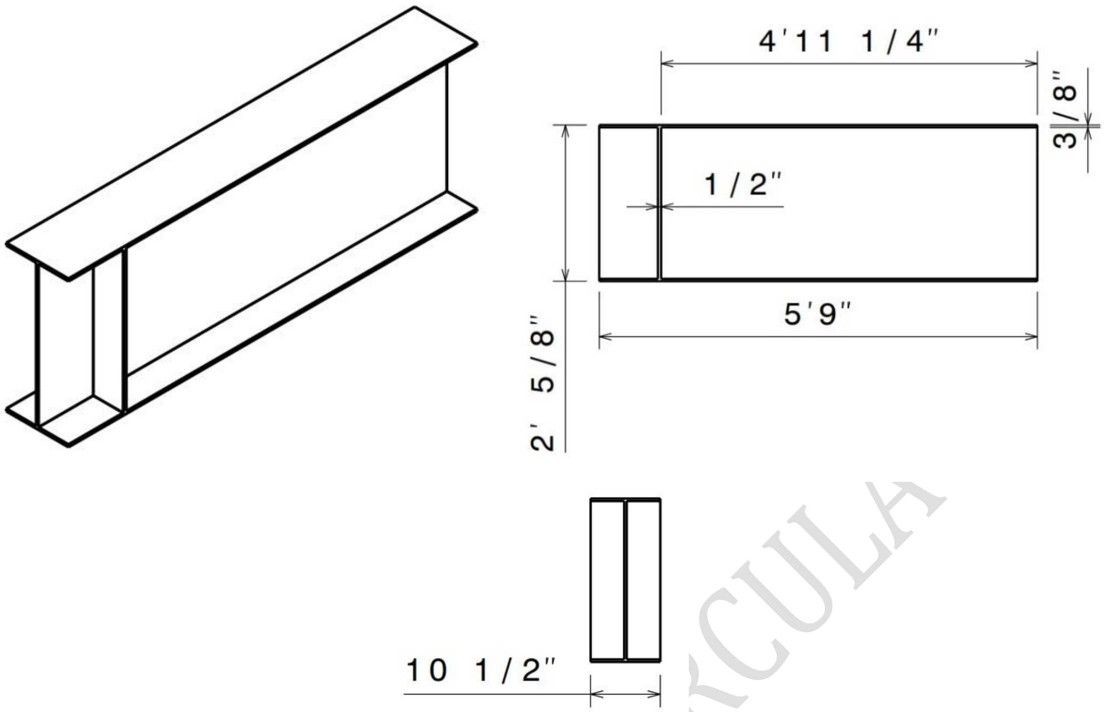


Figure 35 Isometric view, front view, and side view of element S2

6.5.10 Element S3

6.5.10.1 Element S3 (Figure 36) is a steel beam with one of the flanges and part of the web missing. The location allows inspection in elements located far from the ground and one side of the web forces the camera of the UAV to work under overexposed scenarios.

6.5.10.2 Defects covered by this element shall include corrosion, cracks, and deformations caused by impact.

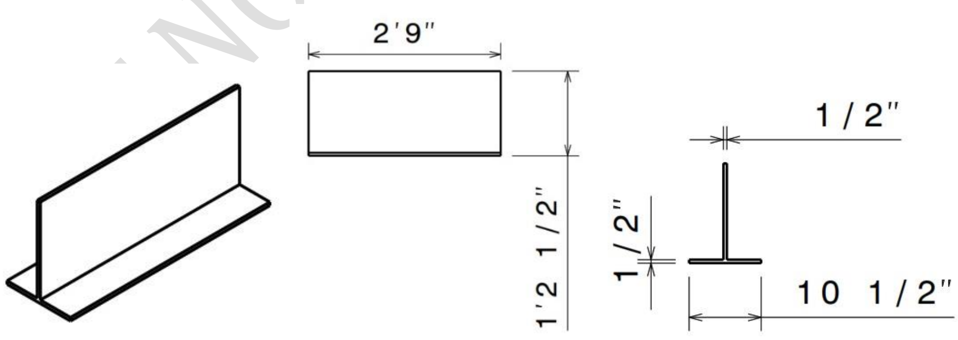


Figure 36 Isometric view, front view, and side view of element S3

6.5.11 Element S4

6.5.11.1 Element S4 (Figure 37) is a steel beam with longitudinal and transversal stiffeners.

6.5.11.2 Defects covered in this element shall include cracks and corrosion.

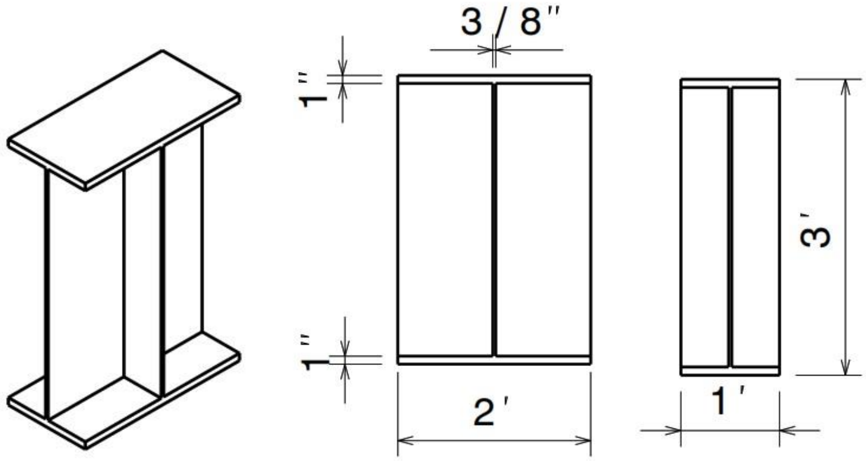


Figure 37 Isometric view, front view, and side view of element S4

6.5.12 Element S5

6.5.12.1 Element S5 (Figure 38) is a steel plate with four holes. The location of the element allows exploring ground effect for elements with small size.

6.5.12.2 Defects covered in this element shall include corrosion and cracks.

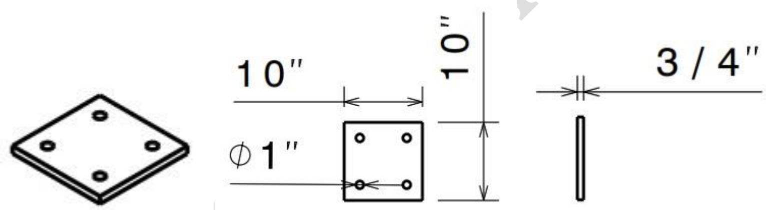


Figure 38 Isometric view, top view, and side view of element S5

6.5.13 Element S6

6.5.13.1 Element S6 (Figure 39) is a small steel beam with paint on the side visible to the UAV. The location of the element allows to explore ground effect for elements with small size and with difficult access due to nearby elements.

6.5.13.2 Defects covered in this element shall include corrosion.

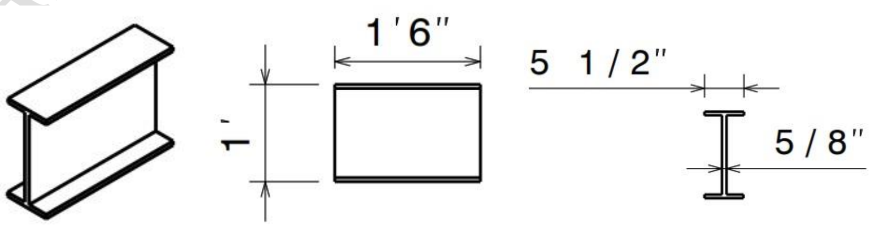


Figure 39 Isometric view, front view, and side view of element S6

6.5.14 Element S7

6.5.14.1 Element S7 (Figure 40) is a steel element with bolts on the sides and rivets on the bottom steel plate facing the ceiling. The location of the element resembles the location where surrounding sections provide difficult access to bolts and rivets during an inspection.

6.5.14.2 Defects addressed in this element shall include corrosion and cracks in rivets and bolts.

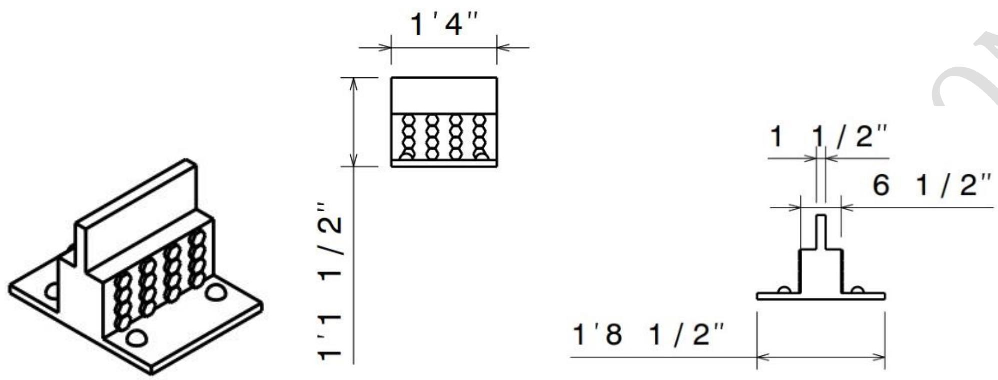


Figure 40 Isometric view, front view, and side view of element S7

6.5.15 Element S8

6.5.15.1 Element S8 (Figure 41) is an element formed by two perpendicular steel plates with shear studs on the floor facing the ceiling. Shear studs have been introduced to address the level of detail not achieved in previous components. The location of the element resembles the location where surrounding sections provide difficult access

6.5.15.2 Defects addressed in this element shall include corrosion and shear studs. At least one of the shear studs should present deformations.

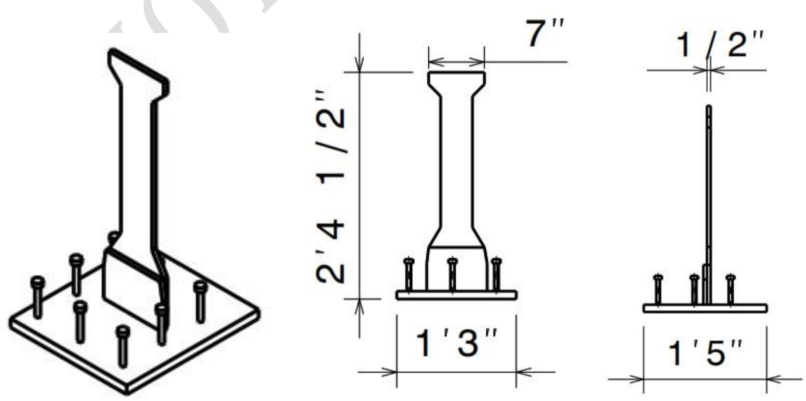


Figure 41 Isometric view, front view, and side view of element S8

6.5.16 Element S9

6.5.16.1 Element S9 (Figure 42) is a pin and hanger evenly divided into two parts. The division of the element is not mandatory for this element but it provides more areas where access is limited.

6.5.16.2 Defects covered in this element shall include corrosion in pin and hanger connections, corrosion in the base metal, and corrosion accumulated in the connection.

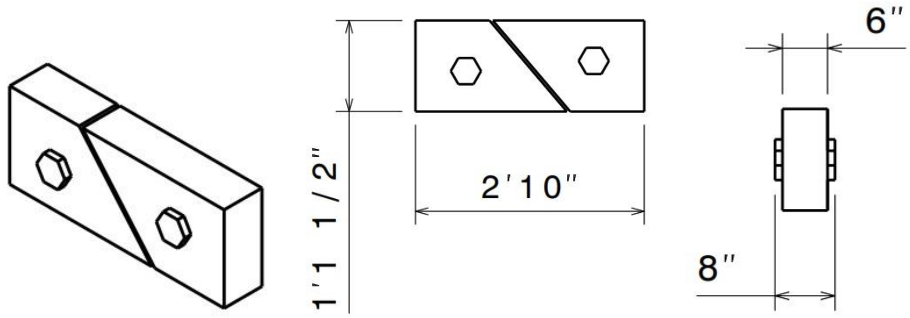


Figure 42 Isometric view, front view, and side view of element S9

6.5.17 Element S10

6.5.17.1 Element S10 (Figure 43) is a steel element with a corrugated pattern section. This element provides different levels of corrosion and section loss. Corrosion has significantly modified the original section. The location of this element provides at least 270° inspection surrounding the element

6.5.17.2 Defects covered in this element shall include heavy corrosion and section loss.

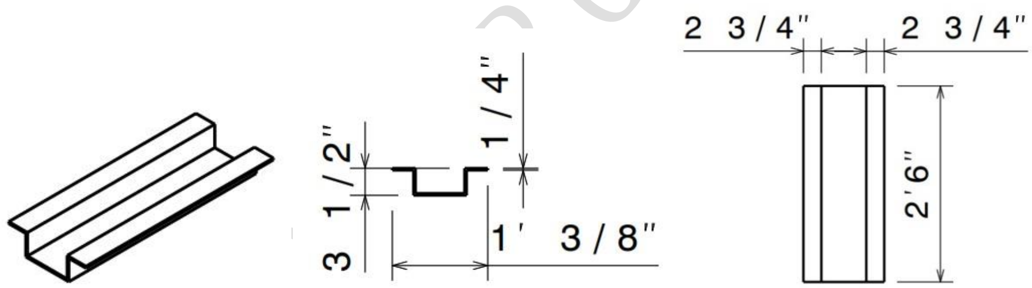


Figure 43 Isometric view, front view, and top view of element S10

6.5.18 Element S11

6.5.18.1 Element S11 (Figure 44) is a steel element with a corrugated pattern section. This element provides different levels of corrosion and section loss. Corrosion has significantly modified the original section. In addition, the location of this element explores ground effect and limits the visual range for inspection.

6.5.18.2 Defects covered in this element shall include heavy corrosion and section loss.

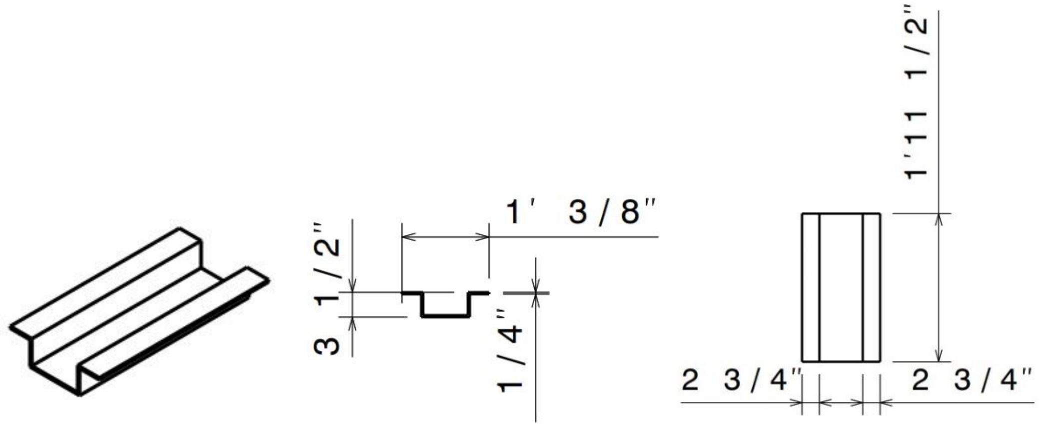


Figure 44 Isometric view, front view, and top view of element S11

6.5.19 Element S12

6.5.19.1 Element S12 (Figure 45) is a steel plate with rivets in the longitudinal direction. The plate accommodates 50 rivets to provide cracks and defects in some but not all of them.

6.5.19.2 Defects covered in this element shall include corrosion and cracks along the rivets.

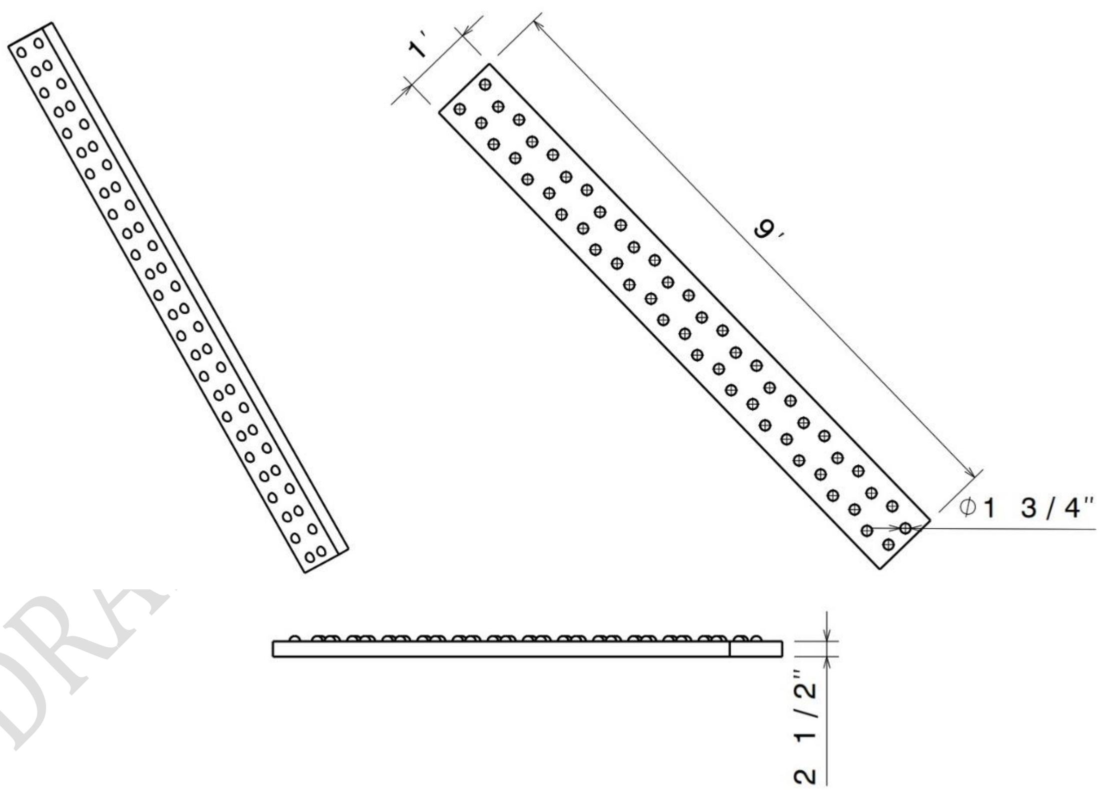


Figure 45 Isometric view, front view, and side view of element S12

6.5.20 Element S13

6.5.20.1 Element S13 (Figure 46) is a thick steel plate with holes in the longitudinal direction. The location of the element resembles the location where surrounding sections provide difficult access but the front face is completely visible to the observer.

6.5.20.2 Defects covered in this element shall include cracks along the holes and corrosion.

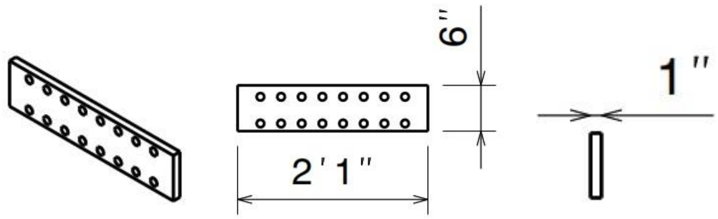


Figure 46 Isometric view, front view, and side view of element S13

6.5.21 Element S14

6.5.21.1 Element S14 (Figure 47) is a steel hanger with a base. The size of the element allows versatility for its location inside the evaluation chamber but it shall be placed where other elements provide difficult access to all its faces.

6.5.21.2 Defects covered in this element shall include corrosion and cracks.

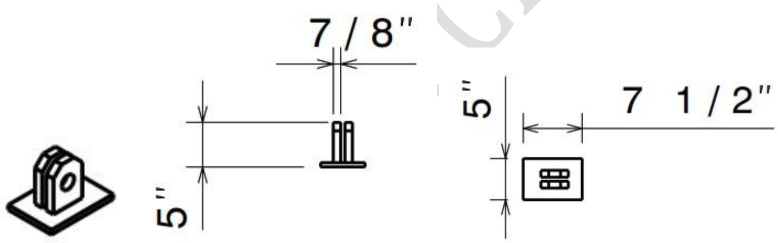


Figure 47 Isometric view, side view, and top view of element S14

6.5.22 Element S15

6.5.22.1 Element S15 (Figure 48) is a tee beam or WT beam. The location of this element provides limited access to one of its faces.

6.5.22.2 Defects covered in this element shall include corrosion and cracks if possible.

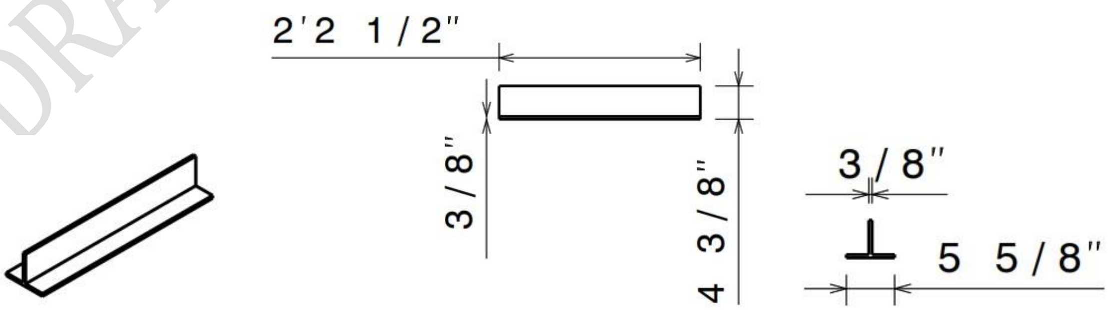


Figure 48 Isometric view, front view, and side view of element S15

6.5.23 Element C1

6.5.23.1 Element C1 (Figure 49) is an element formed by two reinforced concrete L-shaped blocks connected to each other. At their point of contact shear fracture has occurred. The location of this element provides limited access to one of its faces.

6.5.23.2 Defects covered in this element shall include shear cracks in reinforced concrete, exposed rebar and spalling.

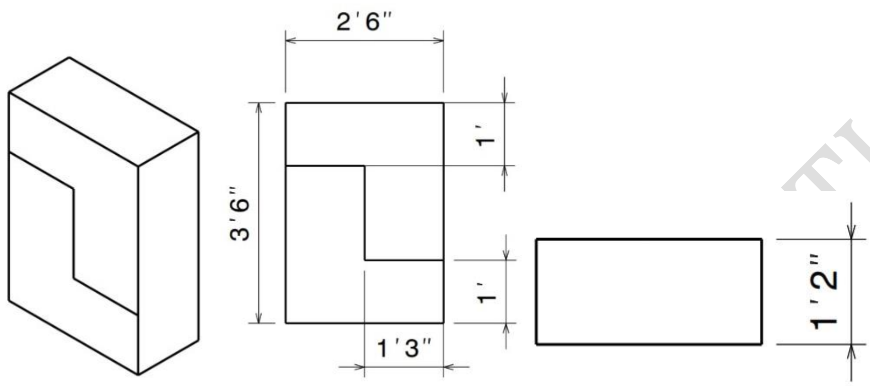


Figure 49 Isometric view, front view, and top view of element C1

7. Hazards:

7.1 No immediate hazards have been identified during this test.

7.2 The test must be stopped and the UAV must be landed if after taking off, the UAV is not hovering itself in place at a distance more than 1 feet 6 inches from the ground, the pilot is not in complete control of the UAV, and the erratic movements of the UAV represent a danger to the pilot or the UAS inside the evaluation chamber.

7.3 No specific path or minimum distance to approach elements inside the evaluation chamber has been provided.

8. Procedure:

8.1 Before the start of the test.

8.1.1 *Preflight Checklist.* The UAS must comply with the checklist presented in Appendix of this standard before starting the test. Some operational procedures included in the checklist are detailed below.

8.1.2 *Identify if the UAS is suitable for the Evaluation Chamber.* The UAS must comply with weight and horizontal dimension limitations presented in section 2 of this standard. In addition, the UAS must fly and maneuver without the need for a GPS signal to fly in an indoor environment.

8.1.3 *Airframe check.* The UAS must fulfill requirements for inspection and maintenance provided by the manufacturer. The UAV must be free of damage in any airframe part including motor, propellers, battery, transmitter, and additional payload. All compartments must be closed before taking off.

8.1.4 *Batteries and data acquisition.* The number of batteries available, label number (a unique number distinguishing a set of batteries), and manufacturer code of the batteries (a unique number provided by the manufacturer to the battery) to be used in the test shall be identified by the proctor and registered in an appropriate form. Any data acquisition aid to be used during the test shall be tested and secured (i.e., camera in place with a SD card or internal memory appropriate to store information).

8.1.5 *Prepare the Evaluation Chamber.* The evaluation chamber shall be verified to have the lighting described in the Apparatus section, 6.1 and 6.2. The evaluation chamber must contain the elements placed at the distances with respect to the walls of the cargo container and with respect to each other specified in this standard. Any foreign object shall be removed from the evaluation chamber.

8.1.6 *Takeoff position.* After the proctor has verified that the UAS is suitable to be evaluated in the evaluation chamber and the UAV does not present any visible damage, the pilot must place the UAS at the entrance of the container in the designated area after any additional calibrations have been performed according to the manufacturer.

8.1.7 The pilot, the visual observer, and/or the pilot in command are not allowed to enter the evaluation chamber under any circumstance before, during, or after the test. The proctor of the test shall conduct any emergency action required to retrieve the UAV from inside the chamber.

8.2 Procedure during the test

8.2.1 *Flight Checklist.* The UAS must comply with the checklist presented in Appendix of this standard before taking off.

8.2.2 *Takeoff.* The UAV shall take off in the designated area and the pilot shall maneuver only from the entrance of the cargo container. The pilot can move freely outside the container and take any position that they consider appropriate to complete the test successfully. A distance of 2 feet to 5 feet from the entrance of the container is recommended to navigate inside the evaluation chamber successfully. The pilot is not authorized to enter inside the container under any circumstance. The proctor of the test shall perform any emergency procedure inside the chamber. The takeoff and landing times shall be recorded in the appropriate form attached to this standard for each battery used during the test. All the information required in the form is presented in the Report section of this document.

8.2.3 *Data collection.* The UAS is authorized to fly to any location inside the evaluation chamber to inspect and gather visual information from all the steel elements, concrete elements, and components inside the evaluation chamber. The test ends when the UAS considers all the necessary information to provide a complete assessment of the elements inside the evaluation chamber have been collected.

8.2.4 *Landing.* Landing is only authorized to be performed in the takeoff point established by the proctor at the entrance point of the evaluation chamber. Hence, if any battery change is required during the test, the UAS must plan accordingly to come back to the takeoff point from any place of the chamber. No takeoff is allowed inside the evaluation chamber unless in emergency cases.

8.3 After the test

8.3.1 *End of test.* The test ends when the inspector considers the UAS has captured all possible defects inside the evaluation chamber and they can be assessed either in real-time flight or in post-processing work.

9. Report:

9.1 This test provides an additional form to collect and report information from the test allowing comparison over time and between facilities for a given UAS, across UAVs, and pilots.

9.2 The following information should be reported on the test form:

9.2.1 Date:

9.2.2 Brand of UAV:

9.2.3 Model of UAV:

9.2.4 Registration number:

9.2.5 Pilot in Command:

9.2.6 Facility name:

9.2.7 Check if UAS complies with dimensions and weight specified:

9.2.8 Check airframe for damage:

9.2.9 Payload attached and compartments checked:

9.2.10 Battery information (label and code):

9.2.11 Test information:

9.2.11.1 Start time:

9.2.11.2 End time:

9.2.11.3 Duration:

9.2.11.4 Notes of each flight:

9.2.12 Additional notes:

10. Precision and Bias:

10.1 This test method is a result of numerical and non-numerical analysis to achieve a minimum level of reliability for UAS used in bridge inspection. The evaluation chamber provides an assessment of different levels of expertise that the tested UAS has under bridge environments. The evaluation chamber has been designed accounting proximity effects and dimensions of common UAVs, providing an objective and fair setting to test most UAS applied in bridge inspection.

10.2 The test allows change of batteries at any time that the pilot considers appropriate to account for inherit bias that the author might have had to design the test, to account for the familiarity of the author and pilot with the evaluation chamber, and for trying it in several trials.

11. Keywords:

11.1 evaluation chamber, bridge inspection, UAS bridge, steel defects, concrete defects.

APPENDIX C

Standard Environmental Temperature Test for Unmanned Aerial Systems used for Bridge Inspection

Table of Contents

1. Introduction

This appendix provides mandatory requirements to perform environmental temperature testing using a controlled environment when evaluating any Unmanned Aerial System for use in bridge inspection.

2. Scope

2.1 The procedures and standards outlined in this document govern any Unmanned Aerial System (UAS) intended for use in bridge inspection.

2.2 The Unmanned Aerial Vehicle (UAV) must fall under the category 'small' defined in the Code of Federal Regulations (14 C.F.R.§107.3). The CFRs define a small UAV as weighing less than 55 pounds (on takeoff).

2.3 The Unmanned Aerial Vehicle (UAV) must have a propeller-tip-to-propeller-tip distance less than the sum of the smallest internal dimension of the testing area plus 1 foot.

2.4 Protective equipment that inhibits the impact of proximity effects in the vehicle when flying (e.g., protective cage, propeller guards, etc.) shall be permitted during the test. For this case, the report shall reflect the use of such equipment.

2.5 The test method does not provide any guidance regarding assessing camera resolution or other forms of imaging sensors or devices attached to a UAV.

2.6 The overall test defined in this appendix is referred to as the 'Environmental temperature test' and is conducted within a controlled environment. Details of the environmental parameters controlled in this test are presented in the following sections.

2.7 This test method is one of the several tests to evaluate overall system capabilities for the inspection of bridges using UAVs.

2.8 The U.S. Customary Units (a.k.a. Imperial Units) are used throughout this document. For values of temperature, the equivalent units in the International System of Units (a.k.a. SI Units) have been provided in parentheses.

3. Definitions

3.1 ***Unmanned Aerial System:*** or Unmanned Aircraft System (UAS), is a system capable of flying under the control of a person who is not present in the vehicle itself. A UAS includes the vehicle, the vehicle's pilot, sensors, and additional features.

3.2 ***Unmanned Aerial Vehicle:*** (UAV) or drone is an aircraft remotely controlled by a computer, a navigator on the ground, or a combination of both, and does not require a pilot to be physically present on the vehicle when flying.

3.3 ***Pilot/Inspector:*** is the human element in the system. The pilot in command is responsible for controlling the UAV to fly and perform different tasks during takeoff, landing, and throughout the mission. The inspector is the individual deciding where to fly, what to focus on, and the data interpretation. The pilot may also supervise the vehicle while under the control of autonomous flight software. The pilot and inspector may be the same individual, but this is not required.

3.4 ***Propeller-tip-to-propeller-tip distance:*** distance between the exterior tip of one propeller and the exterior tip of the opposite propeller, or the element in the UAV located at the farthest from the center of the vehicle in the horizontal plane (rotor, spherical shell, propeller guards, etc.). In most cases this measurement can be easily found by rotating two opposite propellers parallel to each other and measuring the distance between the exterior tips, as presented in Figure 1.

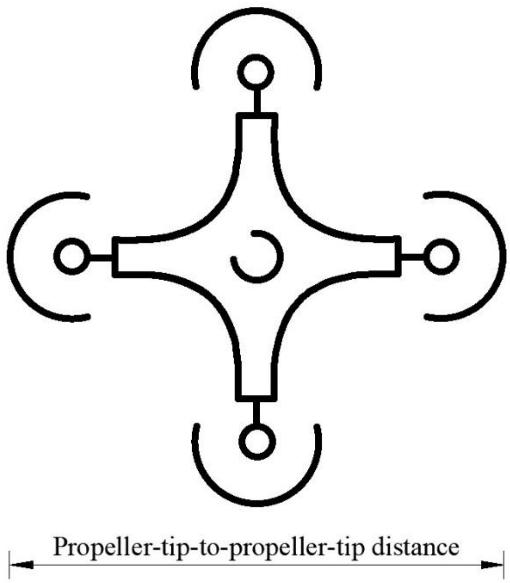


Figure 1 Illustration of propeller-tip-to-propeller-tip distance in a UAV.

3.5 ***Small Unmanned Aerial Systems:*** according to the Code of Federal Regulations, 14 C.F.R.§107.3, a small UAV is a vehicle that weighs less than 55 pounds on takeoff.

3.6 ***Proximity effects:*** drift and changes in the quasi-stationary state of the UAV when hovering or flying caused by its proximity to elements above, below or next to the UAV.

3.7 ***Protective cage:*** a surrounding element, sometimes spherical, attached to the UAV to protect it from impact to nearby objects.

3.8 ***Global Navigation Satellite System (GNSS):*** is a satellite system that provides localization services to a receiver on Earth and part of it is the Global Positioning System (GPS). In this document, the term GPS refers to the GNSS most prevalent and commonly used in the US.

3.9 ***Visual Observer:*** according to the Code of Federal Regulations, 14 C.F.R.§107.3, a visual observer is a person designated by the pilot in command to assist the pilot in command or the person manipulating the controls of the UAS to see and avoid air traffic or objects on the path of the UAS.

3.10 ***Minimum battery power percentage:*** minimum percentage of power in the battery that can be safely reached by hovering and flying the UAV. Safely means without compromising the chemical integrity of the battery. This percentage usually ranges from 0% to 20%, depending on the model and the settings of the UAV. Some models allow the change of this value.

3.11 ***Fully charged battery:*** a battery that has reached the highest charge level as specified by the manufacturer. This limit can be reached by plugging the battery into the original charger provided by the manufacturer and allowing to charge the battery until the battery charger determines it has reached the maximum capacity allowed within safety margins (not always 100%). Batteries shall be charged within the range defined by the manufacturer.

3.12 ***Normal environment conditions:*** for this test, normal environment conditions are defined as those presented in an indoor or outdoor environment where the temperature is 70 °F (21.1 °C) and 45% relative humidity.

3.13 ***Relative Humidity:*** is an environmental parameter that measures the amount of water vapor in the air at a specific temperature compared to the maximum possible water vapor at the same temperature. Ideal relative humidity ranges from 45% to 60%.

3.14 ***'Temperature Test Information' form:*** referred to as the 'test form', is a document attached at the end of this procedure where the pilot/inspector or the visual observer (if any) must provide general information prior to the test (UAV characteristics) and during the test (start time, duration of the test, percentages of the batteries, etc.).

4. Significance and Use

4.1 This test method is part of a comprehensive set of tests applied to UAS by the UAS Validation Center to provide information and system compliance before inspecting structures, particularly bridges.

4.2 This test method provides information regarding the UAS capabilities under temperatures outside normal environmental conditions. Under conditions outside the range of normal environmental conditions, the pilot/inspector shall always follow the recommendations of the manufacturer.

5. Summary of Test Method

5.1 This test method is intended for small Unmanned Aerial Systems (UAS) that comply with weight and horizontal dimension limitations presented in the scope of this standard. This test method presents the process to follow to obtain data when a UAS is hovering under different environmental temperatures. This test method is conducted in an environment with no GPS signal (GPS-denied environment) known as the environmental chamber. This test method can be conducted in chambers that comply with the minimum distances, temperature, and relative humidity values presented in the following sections.

5.2 This test method is conducted in two parts: normal environmental conditions and "cold" conditions, as defined by this standard. They do not need to be performed on the same day to allow the chamber reach a stabile temperature between tests.

5.3 The pilot must be familiar with taking off and hovering the UAS in indoor environments before the start of the test. If necessary, a practice location shall be available for the pilot to demonstrate such competence before the environmental temperature test. Ideal practice locations shall not require any flight authorization (i.e., indoors), and shall be taller and wider than the chamber described in this document (e.g., shed, warehouse, lab space).

5.4 At the beginning of the test, the pilot must be familiar with the chamber, determine the location for take-off and landing, and the airspace where the UAV will be hovering for the duration of the test. The pilot must also familiarize themselves with the area to safely observe and maneuver the UAV at all times.

5.5 Before starting the test, the pilot must check the integrity of the UAV as described by the manufacturer and ensure that all batteries and controller(s) are fully charged.

5.6 The pilot and controller must be inside the chamber at all times and wear proper attire during the test in accordance to the temperature inside the chamber.

5.7 The pilot must use the controller provided by the manufacturer of the UAV and if required an additional device (smartphone or tablet) to record and store flight data automatically generated by the UAV.

5.8 The results provided in this test can be used as a reference for future flights when the UAV is flying under the same payload registered in this test. For that reason, any additional payload or devices shall be registered in the test form.

5.9 The test shall be performed at least one time with a payload that includes all devices necessary to carry a typical bridge inspection at the discretion of the pilot (e.g., camera, protective equipment). The test can be repeated several times to account for additional devices for non-typical bridge inspections such as in the case of night flights that require the use of strobe lights.

5.10 If the manufacturer provides a method to record flight data, the pilot must ensure this data is being stored in the additional device or the internal memory of the UAV before the start of the test. The data obtained must be readable and available to export to common file extensions (e.g., txt, csv, etc.). This data will be used to perform a post-flight analysis and must be delivered to the UAS Validation Center when the test is completed.

5.11 ***The Test:*** the test is performed in two parts. In Part 1, the chamber shall reach normal environmental conditions and in Part 2, the chamber shall reach "cold" conditions. The procedure is the same for both parts of the test except for the required temperature and relative humidity values.

5.12 ***Environmental parameters during the Test:*** the chamber must provide the following temperature and relative humidity:

5.12.1 ***For Part 1:*** a temperature of 70 °F (21.1 °C) ± 2° F (1.1 °C) and relative humidity of 45% ± 5% for the duration of the test.

5.12.2 ***For Part 2:*** a temperature of 20 °F (-6.7 °C) ± 2° F (1.1 °C) and no relative humidity have been provided for this part of the test. Relative humidity can vary due to the low temperature the chamber shall reach but values between 50% and 80% are usually achieved.

5.13 ***During the Test:*** the following procedure is applicable for Part 1 and Part 2 after the chamber has been adjusted to the environmental parameters described in section 5.12. The procedure is as follows.

5.13.1 The UAV shall take off inside the chamber, advance towards a height that shall be at a mid-point between the ceiling and floor. The clock time when the UAV separates from the ground is the start time and shall be recorded in the test form along with the battery percentage of both the controller and the UAV. At the same time, a chronometer shall be started from zero.

5.13.2 The UAV shall hover in place until the minimum battery power percentage has been reached. The minimum battery power percentage can vary according to the manufacturer.

5.13.3 Once the minimum battery power is attained, the pilot shall land the UAV. If the UAV includes software that automatically results in the UAV landing itself when the minimum battery power percentage has been reached, this time shall be recorded. The clock time when the UAV touches ground is the end time of the test and shall be recorded in the test form along with battery percentage of both the controller and the UAV. At the same time, the chronometer shall be stopped and the time presented is recorded as the duration time of the test in the test form.

5.13.4 If the controller reaches the minimum power percentage before all the batteries have been used, the pilot will assess if charging the controller while flying the UAV is possible and safe for the UAS. If not, the test ends. These additional notes must be included in the form.

5.13.5 After landing, the UAV is inspected for any damage and the test continues with the next battery available. The test ends when all the batteries available have been used and the data has been recorded for each of them.

6. Apparatus

6.1 Test Environment: this test method is conducted in an enclosed environment with no GPS signal known as an environmental temperature chamber. The chamber selected must be able to set values of temperature of at least 20 °F (-6.7 °C) ± 2° F (1.1 °C) and 70 °F (21.1 °C) ± 2° F (1.1 °C). In addition, the environment must be able to provide a relative humidity between 40% and 80%.

6.2 The internal dimensions of the test environment have been determined to comply with the minimum spacing surrounding a typical UAS based on proximity effects. The minimum internal dimensions of the chamber shall be:

6.2.1 Width: greater than the sum of propeller-tip-to-propeller-tip distance of the UAV plus 1 foot.

6.2.2 Length: greater than the sum of propeller-tip-to-propeller-tip distance of the UAV plus 1 foot and to provide additional space for the pilot inside the chamber.

6.2.3 Height: greater than the sum of the total height of the UAV plus 3 feet.

7. Hazards

7.1 No immediate hazards have been identified during this test.

7.2 The test must be stopped and the UAV must be landed if after taking off, the UAV is not capable of maintaining a hovering distance of more than 1 foot 6 inches from the ground or the ceiling, the pilot is not in complete control of the UAV, or the erratic movements of the UAV represent a danger to the pilot or the UAS inside the chamber. Erratic movements are defined as displacement of the UAV in more than 6 inches in any direction occurring two or more times in intervals of 30 seconds or less.

7.3 Proper footwear and other personal protective equipment shall be worn to mitigate risk inside the chamber.

8. Recommendations

8.1 When the pilot in command is not familiar with temperature and relative humidity conditions in the testing area, it is recommended to execute trial runs of taking off and hovering in enclosed spaces. The pilot shall closely focus attention on the behavior of the UAV during the first 15 to 30 seconds after taking off and hovering in place. Based on past experiences, this time frame has been the most likely period where a UAV would show issues related to the conditions of its environment.

8.2 To avoid any risks of collision inside the chamber, hovering is recommended to be performed at mid-height between the ground and ceiling but a distance of no more than 3 feet from the ground is needed.

8.3 Before attempting any operations in temperatures outside normal environment conditions, the pilot in command shall always be familiar with the recommendations of the manufacturer.

8.4 The following standard provides a better understanding of the performance of both the battery and the controller in a controlled environment. During previous tests, the results from this standard for a particular UAS show performance characteristics are commonly different from what the manufacturer has provided. Several parameters can play a part in this difference and among the most common ones are: the age of the batteries, use of the batteries, the flight time of the UAS elements, weather conditions, and complexity of the UAS mission.

8.5 During previous 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. For that reason, it is recommended to only expose the batteries to the environment when they are going to be used.

8.6 Additional payload can increase the risk of damage to the battery and the pilot in command shall always check the specifications of the manufacturer before adding extra load to the UAV. Further, elements such as lights for night flights, protective cages, and vision devices can significantly reduce the flight time.

8.7 The dimensions of the chamber used in the development of this standard are presented in the following section along with an isometric and elevation view in Figure 2 and Figure 3.

8.7.1 Internal width of the testing area: 9 feet 11 inches.

8.7.2 Length of the testing area: 20 feet 6 inches.

8.7.3 Height of the testing area: 8 feet 9 inches.

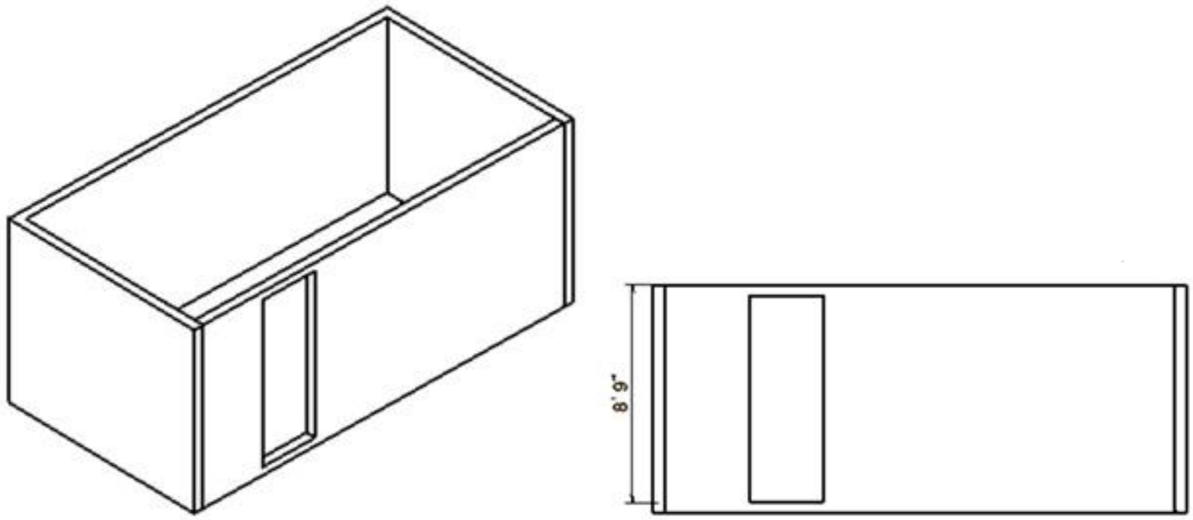


Figure 2 Isometric view and elevation view of environmental temperature chamber.

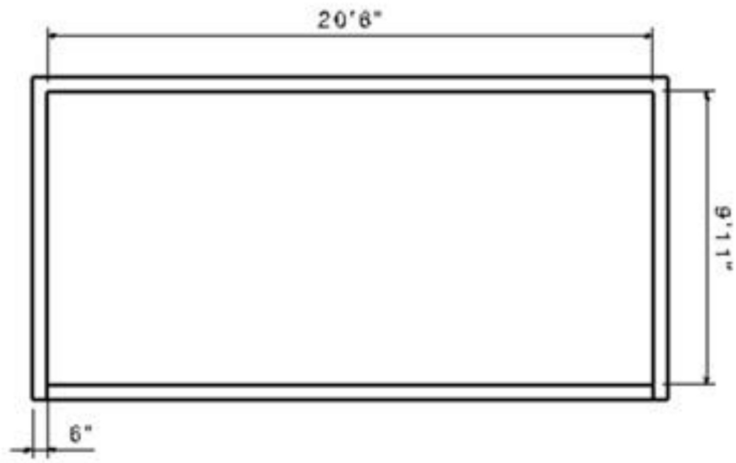


Figure 3 Top view of environmental temperature chamber.