Progress Report

TPF 5-387

Development of an Integrated UAS Validation Center

Purdue University

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Project Background and Objectives

Unmanned Aerial Systems (UAS) have the potential to drastically change how civil infrastructure is inspected, monitored, and managed. In the context of this document, a UAS is comprised of an Unmanned Aerial Vehicle (UAV), the scanning technology it carries, and the pilot. Deployment of UAS in areas such as bridge inspection and accident reconstruction will likely have far-reaching impacts and evolve over time, with new uses and users emerging as technology matures. With new technology, limitations exist until new protocols are established and industry must move forward with an appropriate level of caution. For example, speculation regarding the ability of a UAS to replace a human bridge inspector is frequently observed in trade magazines, presentations, and in the literature. With no standard tests to verify such claims, agencies are left to rely upon vendor’s promotional material when making decisions about UAS deployment.

This pooled-fund study proposes to develop the standards, protocols, and testing requirements that a given UAS must meet and demonstrate for a particular application. As an example, considerations regarding UAS deployment for bridge inspection may include (but are not limited to) the following:

- Safety in constrained locations where line of site is limited
- Imaging system performance in poorly lit environments
- Control of the UAS while flying between large steel girders
- Adequate resolution of the imaging system for detecting the damage of interest

The objectives of the study are two-fold:

- Development of the specific criteria a given UAS must meet for each particular application.
- Determining how to validate that a given UAS meets the required criteria.
- The current industry is unregulated with regard to establishing the required level of performance for UAS in civil engineering applications. The results of this study will be the development of the performance measures and validation criteria that agencies can use when making decisions about deployment of UAS in the context of civil engineering.

This progress report presents detailed discussion regarding three primary topics:

- Proposed testing procedures developed to date as related to UAS.
- A discussion of important issues related to camera specifications and associated testing of such are also presented.
- Various factors the RT believes need to be considered by a UAS team prior to beginning a bridge inspection related to flight operations related to local turbulence adjacent to bridge structures.

The RT plans to schedule an on-line webinar/meeting to review the results obtained to date and discuss the next steps moving forward with the Project Panel in the mid-June time frame.

General Approach to Development of the Proposed Testing Procedures

In this section, proposed testing procedures for UAS evaluation are presented. Note, the term Unmanned Aerial Aystem "UAS" in the context of this project refers to all components associated with using drones for inspection or other forms of measurement/detection/investigation. Thus, it includes not only the unmanned aerial vehicle (UAV) but also the pilot and the scanning technology (e.g., camera or sensors). All of these taken together comprise the UAS to be evaluated. A given UAV platform with one cameral system may not be able to capture the same quality data as the exact same UAV platform with a different camera, or different pilot. The RT believes all testing and associated qualification or certifications must be applied to the UAS and not an individual pilot, UAV, or sensing system.

Hence, the testing developed targets both the UAS as well as individual components, which may include the UAV. For example, based on the feedback from the partner states, it was determined that some test which evaluates a minimum level of performance during cold temperatures of a given UAV platform must be provided. However, in some ways, this performance can be evaluated to a certain degree independent of the pilot or application. Hence, the cold temperature performance test has been developed with a narrow objective. Other testing is more holistic and will evaluate the pilot, UAV, and sensors as a complete unit (i.e., the UAS).

Concept of a UAS Obstacle Course for UAS Evaluation

A challenge that has been identified by the research team (RT) during the project is the need to ensure that all testing is

1) Repeatable anywhere in the country
2) Consistent for all systems being evaluated as much as possible,
3) Reasonable,
4) Realistic.

For example, the facility and specimens at the Center for Aging Infrastructure (CAI) and S-BRITE Center at Purdue University present an excellent opportunity for evaluating the capabilities of UAS. Both CAI and S-BRITE easily satisfy items 3 and 4 above. However, depending the time of year and weather, item #2 can be difficult to satisfy. Further, item #1 is also difficult to satisfy since all testing would need to be performed at Purdue University. The RT believes that such a requirement is not very attractive and may result in non-uniform testing results. For example, while one UAS may be evaluated in calm 70F weather, another could be evaluated in 30F degree windy and snowy weather. Obviously, the conclusions regarding the performance of each system would be different.

Hence, the RT has explored the concept of a standardized test (or tests) that attempts to evaluate a selected number of performance characteristics coupled with real-world testing in a realistic environment. This has resulted in a two-part performance test. The first part or part of the test would be standardized with an established set of constraints. This would include flying the UAV, meeting specific criteria (e.g., minimum camera characteristics), and possibly a written type of test for site evaluation (this will be discussed in more detail). The second part includes a real-world evaluation that is also weighted in the scoring of the UAS. This second part would involve an actual flight say, at a bridge at S-BRITE or at a bridge available to the owner (or whatever is deemed representative by the evaluator) under a set of real-world conditions that fall within a specified range. For example, the temperature must be between say 60F and 80F degrees and winds less than 20 mph with no precipitation.

The concept is somewhat similar to how pilots are evaluated in both a flight simulator (standardized and repeatable) but also with an instructor using a real aircraft in an actual flight situation. In such tests, a portion is controlled and repeatable for all students while the in-situ test will be subjected to variations in weather (*within reason*) that affect the pilot's performance.

Part I - Controlled Environment Performance Test

For this part of the test, the UAS would be evaluated in a controlled environment under a set of well-defined conditions. The RT has developed the concept of an obstacle course that would allow various performance characteristics of the UAS to be evaluated in an objective and repeatable way. It was also determined that this artificial environment should be something that can be fabricated rather easily and duplicated so that multiple such courses could be created and distributed across the country. The RT has concluded that a very cost effective and versatile solution is to utilize commonly available shipping containers for the application. A given container can the be outfitted with a standard set of "obstacles" and specimens that are tailored to testing a UAS over a wide range of performance attributes. Since such containers are made specifically for shipping, they can easily be loaded and unloaded on trucks and moved form location to location as needed for testing.

Figure 1 illustrates the concept of various illustrative components installed within the container along with possible dimensions of the specimens. The basic shapes included various surfaces commonly found on bridges, such as concrete, steel, wood, pavements, etc. The geometries also model such items including flat surfaces, curved surfaces, cross frames, and various connections in bridges. Further, items of interest can be placed on the floor, walls, and ceiling to evaluate camera capabilities on various surfaced. The individual components would be designed so that a variant of geometric constraints can be varied. For example, the layout of the crossframes would be designed so that they can be adjusted to accommodate various UAV sizes as well as different crossframe layouts. The overall size and clearances would also be variable as needed.

Since the system is enclosed the environment can be completed controlled. Hence, there will be no wind or precipitation that can be cited as influencing the results of the test. Since the geometry itself is also standard, each UAS will be evaluated under the same geometric conditions. Further, the temperature can be maintained within a rather tight range, say 60F to 70F. (*Note a separate test will be used to evaluate the UAS performance under cold weather operations as discussed below*.) Since the entire unit being enclosed, lighting can also be completely controlled from 100% dark to various levels of ambient internal lighting provided to evaluate camera capabilities and pilot navigation skills. Finally, the steel enclosure ensures the testing is performed in a GPS denied environment, which is critical in many applications in bridge inspection. In short, the first part of the test is identical for all UAS to be evaluated

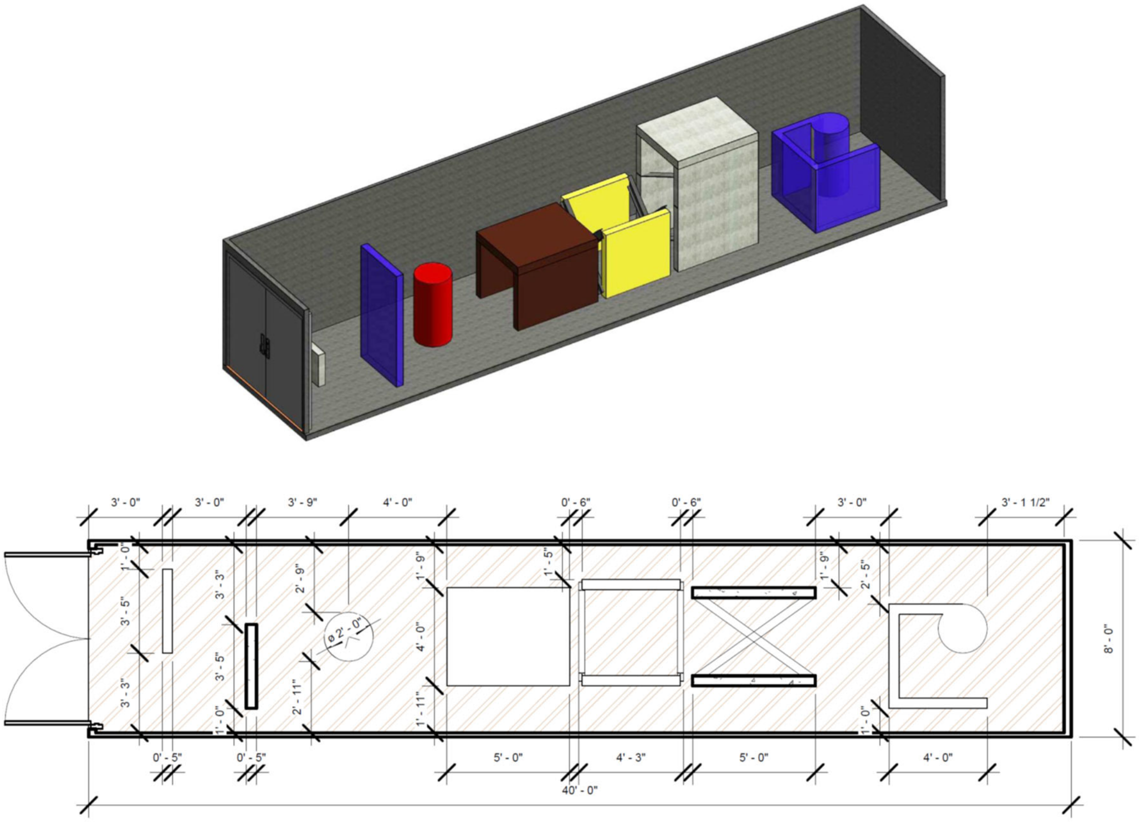

Figure 1 – Proposed draft layout of obstacle course

Part II - Uncontrolled Environment Performance Test

The second part of the performance test would include an on-site evaluation using bridges(s) or specimens out of doors. These bridges (or other items) would need to include characteristics and situations that an owner determines to be representative of their needs. For example, the S-BRITE Center maintains several bridges and bridge components with various types of damage that are ideal for this testing. Further, there is no risk to the public as these specimens are no located near traffic. However, as an alternative, an owner can identify a structure or feature that can be used to performance test in a real environment. Such a test could utilize a building, bridge, or frame that contains parts of structures that would be typically inspected in the field. In other words, it would not *necessarily* have to utilize a structure that carries or is over live traffic. To ensure that the testing is reasonably uniform, the RT proposed to develop some basic guidelines for such tests that are anticipated to include:

- Temperature ranges for testing
- Wind speed ranges for testing
- Overall specimen and feature type to be included
- Attributes for inclusion (e.g., corrosion, cracking, steel, concrete, etc.)
- Other?

Evaluation of Results from Part I and Part II

After completing both parts of the testing, the individual being tested would provide a written report of the damage detected as well as provide specific information requested. For example, during the testing within the container, there will be specimens with specific damage that has been accurately quantified ahead of time, such as the length of a crack or area of paint damage. The report would need to provide an estimate of the same quantity, which would then be compared to the known value. A series of such defined tests would be included in both the controlled and uncontrolled environment tests. Criteria would be developed to score the given UAS for both the Part I and Part II tests to arrive at a final score. The exact scoring for each performance factor will be developed as the parameters are defined and weighted appropriately. Obviously, the weight assigned to a given parameter is somewhat subjected, but using expert elicitation, reasonable scoring parameters can be developed.

At present, the RT requests the reviewers to provide comments on the overall concept and not be overly concerned about the layout of the illustrative example. For example, is the concept reasonable and if so, what items would the panel members feel would be beneficial to include in such a standardized test?

Standardized Temperature Test

During the project kick-off meeting, it was concluded that a standard test in which the temperature is controlled is needed so that a given UAS can be demonstrated to meet a minimum flight time under specified temperatures. As the ambient temperature drops, batter life can be significantly impacted corresponding to shorting mission time (active inspection time). This will result in overall increased time on site corresponding to increased costs for traffic control etc. While decreases in battery life are a fact associated with current technology, the decrease in life should be documented and available to owners so there are no surprises while on site. At present, three tests are proposed corresponding to three different temperatures. The target temperatures are 32, 70, and 100 deg. Fahrenheit. For these tests, the UAS would be expected to hover while streaming video within a suitable chamber in which the temperature is maintained. The duration of the flight time would be recorded and documented in the test report. Prior to beginning the test, the UAS and batteries would be brought to the same temperature as the chamber. Hence, a soak time would be required to ensure batteries are not "warm" at the beginning of the test. A proposed outline of the test is provided in Appendix A of this progress report.

During the kick-off meeting, it was determined that a minimum flight time of 20 minutes at 30 degrees should be specified. At present, this time will be assumed as the pass/fail limit, but can be easily changed by individual owners. Fortunately, this test is not as subjective and, in some ways, could be considered as a gateway test. In other words, if a given platform fails this test, there may be no need to conducted further testing. However, for some owners who may choose to limit the use of a given (or all) UAS inspections, this test may be more informational than pass fail.

Other Tests and Requirements Under Development

While Parts I & II of the obstacle course testing will be very useful in evaluating many individual parameters of the UAS holistically, the RT believe it is critical to have a few additional tests and/or requirements on documentation to be provided by the inspection firm or equipment supplier. Specifically, it is proposed that the UAS meet at least minimum set specified criteria are met for the pilot, UAV, and sensing system. Examples of a few of these criteria, include

- Minimum licensing and experience level of the pilot.
    - Demonstrated skills regarding understanding of current FAA rules and understanding of requirements to operate in various levels of airspace classification.
- Minimum operational characteristics of the UAV:
    - Operation requirements in a GPS denied environment;
    - Actions taken by the UAV when signal is lost;
    - Ability to "geo-tag" images within a specific tolerance.
- Minimum sensing capabilities associated with cameras such as:
    - Zoom capacities;
    - Artificial lighting provided;
    - Color resolution;
    - Contrast resolution

Minimum Sensing Capability Evaluation for Cameras

Progress has been made in the development of criteria to assess claims or stated capabilities associated with cameras and video systems. The RT believes it is critical to have some way to confirm such claims to ensure owners have a uniform standard by which to compare different systems and to identify when "high" end systems are needed for some applications while more common systems are adequate for other applications.

Introduction

Image-based inspection of bridges depends on the quality of the captured images, which are defined/controlled by several resolution components; namely, geometric resolution, spectral resolution, radiometric resolution, and temporal resolution. Below is a brief description of these different resolution aspects and how they impact one's ability to identify defects in the captured images.

- *Geometric resolution* describes the ability of the imaging system to detect fine spatial details (i.e., size wise details). For example, how wide a crack should be in order for it to be detected in an image is controlled by the geometric resolution of the imaging system.
- *Radiometric resolution* describes the ability of the imaging system to detect fine changes in the incident energy onto the light-sensitive elements (pixels) of the imaging system for a given wavelength band. For example, the ability of the imaging system in discerning details in poorly lit regions depends on the radiometric resolution of the imaging system.
- *Spectral resolution* describes the ability of the imaging system to identify fine changes in the wavelength of reflected light from the objects. For example, imaging systems with higher spectral resolution might allow for the identification of sub-surface corrosion, as it would have different reflectivity pattern in different wavelength bands of the spectrum.
- *Temporal resolution* describes the ability of the imaging system to identify temporal changes in the imaged objects. For example, the ability to identify exactly when a crack started to emerge depends on the temporal resolution (i.e., how frequent the images were captured).

Since this research is mainly focusing on using entry-level UAS units equipped with RGB cameras (i.e., cameras with only three spectral bands – Red, Green, and Blue), the RT is mainly focusing on the geometric and radiometric resolution aspects of the imaging systems. The temporal resolution is only controlled by how frequent an imaging campaign is conducted. Therefore, it will not be discussed further as it does not depend on the specifications of the imaging system. The discussion below describes the factors controlling these resolutions.

1. The geometric resolution of the imaging system is controlled by several factor including the lens focal length, pixel size, camera-to-object distance, aberrations, diffraction, depth of field, depth of focus, and motion blur. With current technical advances in the imaging systems (even for commercially available ones), the impact of aberrations on the geometric resolution is kept to a minimum. The impact of the diffraction, depth of field, and depth of focus on the captured images can be controlled through the manipulation of the camera aperture size while considering the constraints imposed by the lighting conditions. Therefore, the key remaining factors affecting the geometric resolution are the lens focal length, pixel size, and camera-to-object distance. The impact of these factors is summarized in what is known as the Ground Sampling Distance (GSD), Equation 1. An illustration of the GSD is also provided in Figure 2.

$$GSD = pixel\ size * \frac{camera\ to\ object\ distance}{focal\ length} \qquad (1)$$

2. *The radiometric resolution* is quite critical when inspecting objects in a poorly lit environment. The radiometric resolution is quantified by the dynamic range, which depends on the number of bits per pixel for a given wavelength band of the imaging system, Equation 2. For example, an imaging system with 8 bits per pixel in a given waveband, the incident radiation on such band can be quantized into 256 shades of gray values. The higher the dynamic range, the better the ability of the imaging system to identify small changes in the incident radiation.

$$Dynamic\ range = 2^{number\ of\ bits\ per\ pixel\ in\ a\ given\ wavelength\ band-1} \quad (2)$$

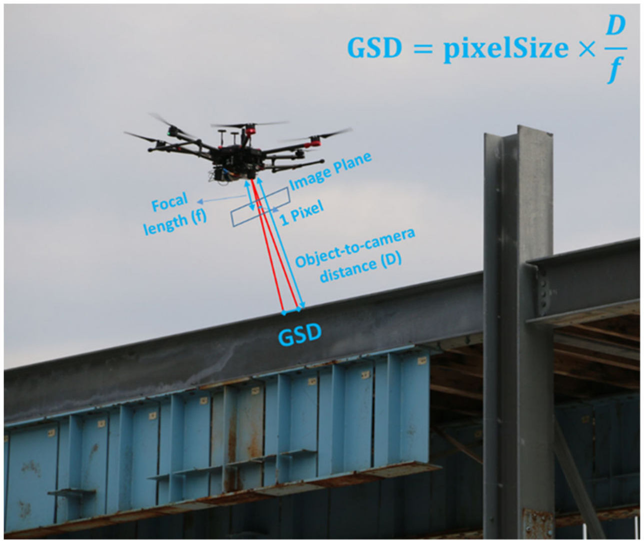

Figure 2: An illustration of the different factors affecting the Ground Sampling Distance (GSD) of an imaging system (photograph at S-BRITE Center)

Geometric Resolution Investigation at S-BRITE

To investigate the combined effect of all the factors on the geometric resolution of an imaging system, we conducted several experiments at Purdue's Steel-Bridge Research, Inspection, Training, and Engineering (S-BRITE) Center. For this investigation, we used a DJI-M600 UAV equipped with the following units: 1) Sony α 7RI digital camera, 2) GoPro digital camera, 3) Velodyne VLP32C LiDAR, and 4) APX 15 Global Navigation Satellite System/Inertial Navigation System (GNSS/INS), Figure 3. As mentioned earlier, the GSD is impacted by the imaging sensor specifications (i.e., lens focal length and pixel size) as well as the camera-to-object distance. The GNSS/INS unit is mainly used for the geo-tagging of the imaging sensors (i.e., determine the camera position and orientation for each exposure). The LiDAR unit on the other hand is used to determine the position of the different objects in the field of view of the imaging sensors. Thus, the GNSS/INS and LiDAR units provide the necessary information (camera-to-object distance) for evaluating the GSD of the imaging system. Example images and the respective GSD values are shown in Figure 4. Together with the hardware integration, a visualization environment is developed to allow for panning through the captured images looking at a specific element of the imaged structure at different camera-to-object distances. The main purpose of this environment is evaluating the information content (level of details) that could be identified given different GSD values. Another advantage of the developed visualization environment is allowing for the inspection of the same element of a bridge at different epochs. In the next phase of the research, we will be using the same visualization environment to evaluate the impact of different lighting conditions on the information content in the captured images with varying GSD values.

Current Progress Related to Camera Evaluation Test Development

The team will continue with capturing more datasets to evaluate the impact of GSD and lighting conditions on the captured images. Moreover, we will image specimens with specific structural defects (e.g., cracks, corrosion, rust) to evaluate the ability of detecting such artifacts. In addition, to quantify the combined effect of geometric and radiometric resolutions, we will take images of a resolution chart (an example of such chart is shown in Figure 5).

Figure 3: Illustration of the UAV system flown over S-BRITE for Geometric Resolution investigation

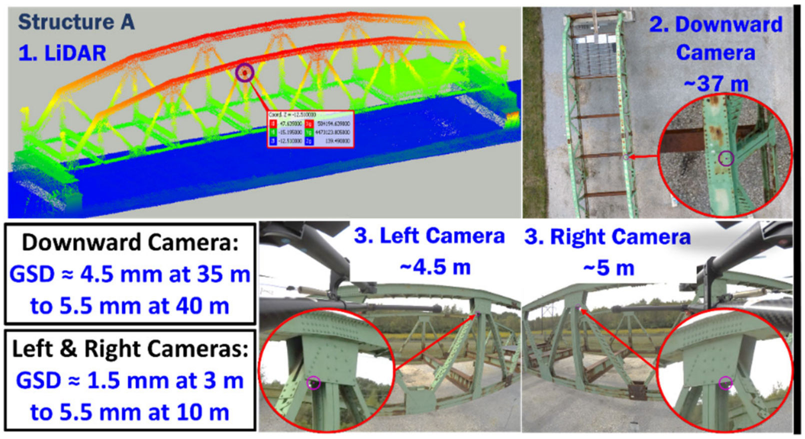

Figure 4: Sample images at S-BRITE and corresponding GSD values

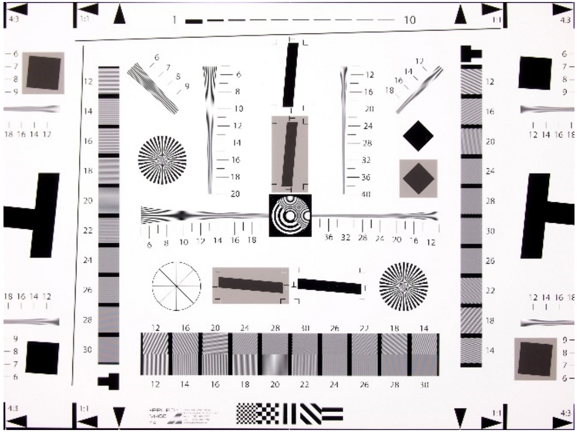

Figure 5: Sample Resolution Chart

Effects of Bridge-Airflow Interactions on UAS-Based Bridge Inspection

INTRODUCTION

UAS-based bridge inspections can rarely be scheduled for and conducted under ideal environmental conditions, including wind velocities, temperature, and ambient lighting conditions. It is therefore important to conduct simulation studies that will lead to a better understanding of the effects of variations in these conditions on such inspections.

Aerodynamic interactions with large-scale structures have long been considered in structural and material science fields. Many studies have been completed with regard to how structures such as bridges and the interacting airflow behave, with focus maintained on the impact on the bridge structure. While structural analysis and aeroelastic effects are fundamental pieces of bridge-airflow interactions, shifting the focus toward the behavior of the downstream flow itself can give insight into how flights of Unmanned Aerial Systems (UAS) in the vicinity of these structures are ultimately affected.

It is the purpose of this research to investigate how external airflow surrounding a bridge could create zones for caution that would necessarily restrict bridge inspection flights. A UAS pilot could be made aware of these zones, giving the inspector a chance to take preventive action in order to facilitate a safe and thorough inspection. A simulation of a common overpass bridge model was developed, and consistently indicates that areas of moderate to severe wind shear and adverse circulation are experienced near various components of the model. A further discussion of the implications of the results is presented here to illustrate how the flow modeling might suggest the need for UAS operational criteria when performing bridge inspections.

This report will identify those aerodynamic interactions that may require caution on the part of the UAS inspection pilot. It is important to propose potential best operating practices that might suggest how UAS are best able to operate in proximity to bridges for the purpose of safety inspections. To adequately determine a set of appropriate flight standards, it is important to consider the precise conditions to which a UAS will be subjected within close proximity to bridges in all types of terrain.

Federal Aviation Administration (FAA) regulations related to operation of UAS in unpredictable flight conditions have not been established. Changes in wind velocity and overall airflow characteristics can subject UAS to potentially hazardous conditions that may inhibit their ability to complete required tasks for bridge inspections. In a discipline in which successful performance of inspection tasks are absolutely critical with respect to maintaining transportation safety, it is important that UAS operators be prepared to experience numerous varying environmental conditions associated with the structures under inspection. In addition to improved pre-inspection preparation, the inspector and operator will benefit in knowing exactly which conditions might make it difficult or impossible to operate the UAS for inspection purposes.

OVERVIEW OF DOWNSTREAM FLOW

Flow downstream from a bridge structural cross section can be easily visualized using conventional computational fluid dynamics techniques. As shown in Figure 6, turbulence effects are greatly increased at the trailing edge of the bridge section. Compressed flow occurs at the leading edge, and a sharp gradient of wind speed occurs above and below. Additionally, areas above and below the bridge are exposed to varying pressures as a result of the vortex-induced vibration (VIV) as the bridge oscillates [1].

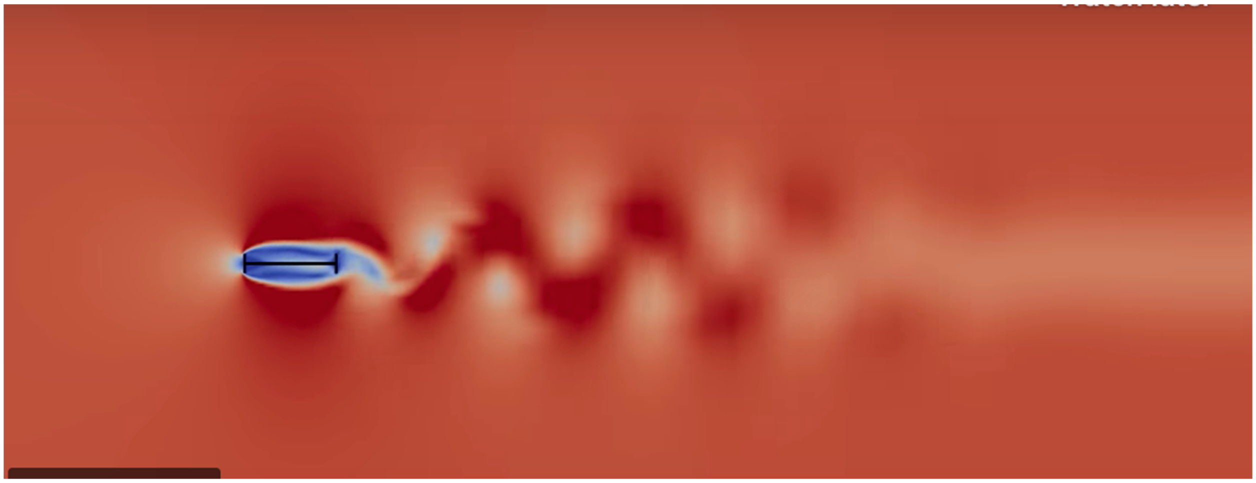

Figure 6. CFD Depiction of airflow over a 2D bridge cross section.

Current literature suggests that there is a critical wind speed at which these oscillations become unbounded (a grave problem concerning bridge stability, but for this research it will also have high impact), and another higher wind speed at which the oscillations become bounded again. An implication of this flow analysis is that areas of wind shear could exist above and below the bridge deck, especially when moderate- to high wind speeds are present. The aerodynamic no-slip boundary condition suggests that the velocity at bridge surfaces are identically zero, and thus a layer of increased velocity exists [2]. At some point, this velocity layer increases to a point at which no aerodynamic effects of the bridge are experienced; however, other effects such as the existence of heat-induced updrafts can alter the operational stability of the UAS.

SIMULATION STUDY

Simulation Methodology

The simulation study was conducted in Solidworks Flow Simulator, which facilitates the creation of aerodynamic models designed specifically for the purposes of this research. A double-bridge deck model was created, as this type of bridge is commonly found in interstate overpass bridge infrastructure. Such bridges are typically constructed of materials including as steel-reinforced concrete, concrete, and steel of varying degrees of thickness. This research will focus, however, on the geometry of the bridge. The surface roughness of the bridge is set at 3 mm, a roughness characteristic that is common for concrete and asphalt aggregates [3].

The airflow in the simulation is set to range from velocities of 3 knots to 20 knots. This range was chosen as it is typical when operating UAS around bridge structures. Most UAS platforms are capable of flying at top speeds between 25-35 miles per hour [4]. This top speed is considered to also be the maximum wind velocity at which the UAS is able to operate. However, it is commonly recommended that a UAS operate in maximum wind velocities below their maximum operating speeds, as doing so substantially reduces the risk of an in-flight loss of control. Because of this, the top speed analyzed was chosen to be 20 knots, or 23 miles per hour. Wind velocities above this range are not feasible for UAS operations and would be expected to show results consistent with the findings of higher wind speeds in this simulation. Simulations were run for various velocities, and the results were compiled as summarized below.

Simulation Results

The simulation results showed consistent findings that moderate- to high wind velocities create areas of substantial wind shear in addition to pier-induced circulation. The boundary layer created by the bridge deck extends a few meters above the deck. This causes a velocity gradient ranging from occasional negative wind velocities to the full velocity of the airflow. Figure 7 shows a screenshot of the simulation results for a 9-knot wind velocity, with areas of wind shear noted and circulation depicted.

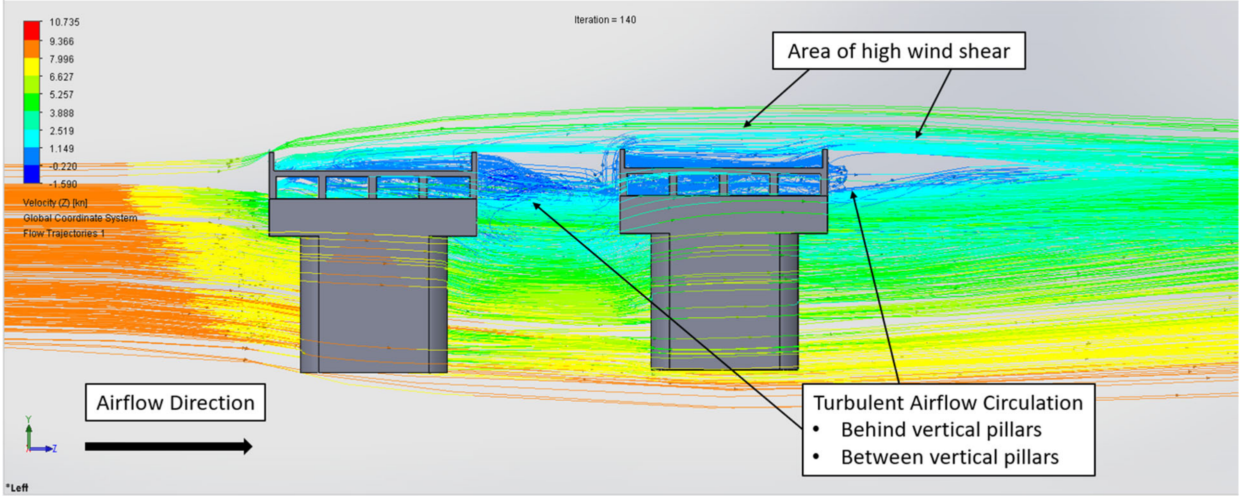

Figure 7. Profile bridge view, airflow simulated at 9 knots.

The results show that at 9 knots, an area of well-formed circulation is present behind the bridge deck. Most notably, this circulation is pronounced greatly at areas where the bridge piers meet the bridge deck. Further simulations of greater wind velocities were completed, the most extreme of which resulted from the 20-knot wind velocity test. Figure 8 shows the 20-knot results.

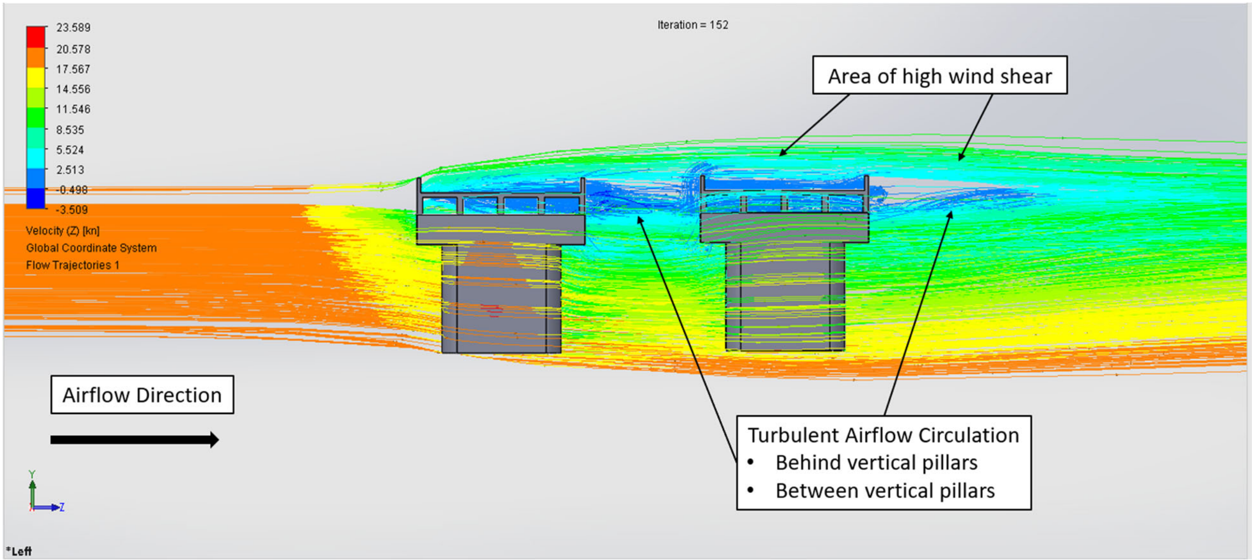

Figure 8. Profile bridge view, airflow simulated at 20 knots.

Again, areas of flow circulation are seen behind the bridge decks. The results are seen to be much more turbulent in nature, which is expected with higher wind velocities. Pier-induced circulation is also noted. This pier-induced circulation results from the obstruction of the airflow, and is magnified by the existence of the second bridge pier. It is interesting to note that the wind velocity has a pronounced effect on the intensity and characteristics of the flow circulation. At lower speeds, the circulation is well-formed. The circulation moves at a low rate relative to the external airflow; however, it does create a low-pressure pocket that would make UAS flight unpredictable and potentially unstable. An image of this circulation and the difference of airflow velocity is shown in Figure 9.

In addition to the circulation, the areas of wind shear are considerable. As mentioned previously, this wind shear is created by the obstruction of the airflow, the no-slip boundary condition, and higher airflow velocities. The 20-knot airflow simulation shows a significant shear resulting from a jump from an adverse flow of -0.499 knots to a forward flow of 14.556 knots. This almost 15 knot difference is not surprising, as the nature of the bridge's shape was predicted to create these large areas of wind shear. For lower velocities, this wind shear is still present; however, its magnitude is reduced with the reduction in wind velocity.

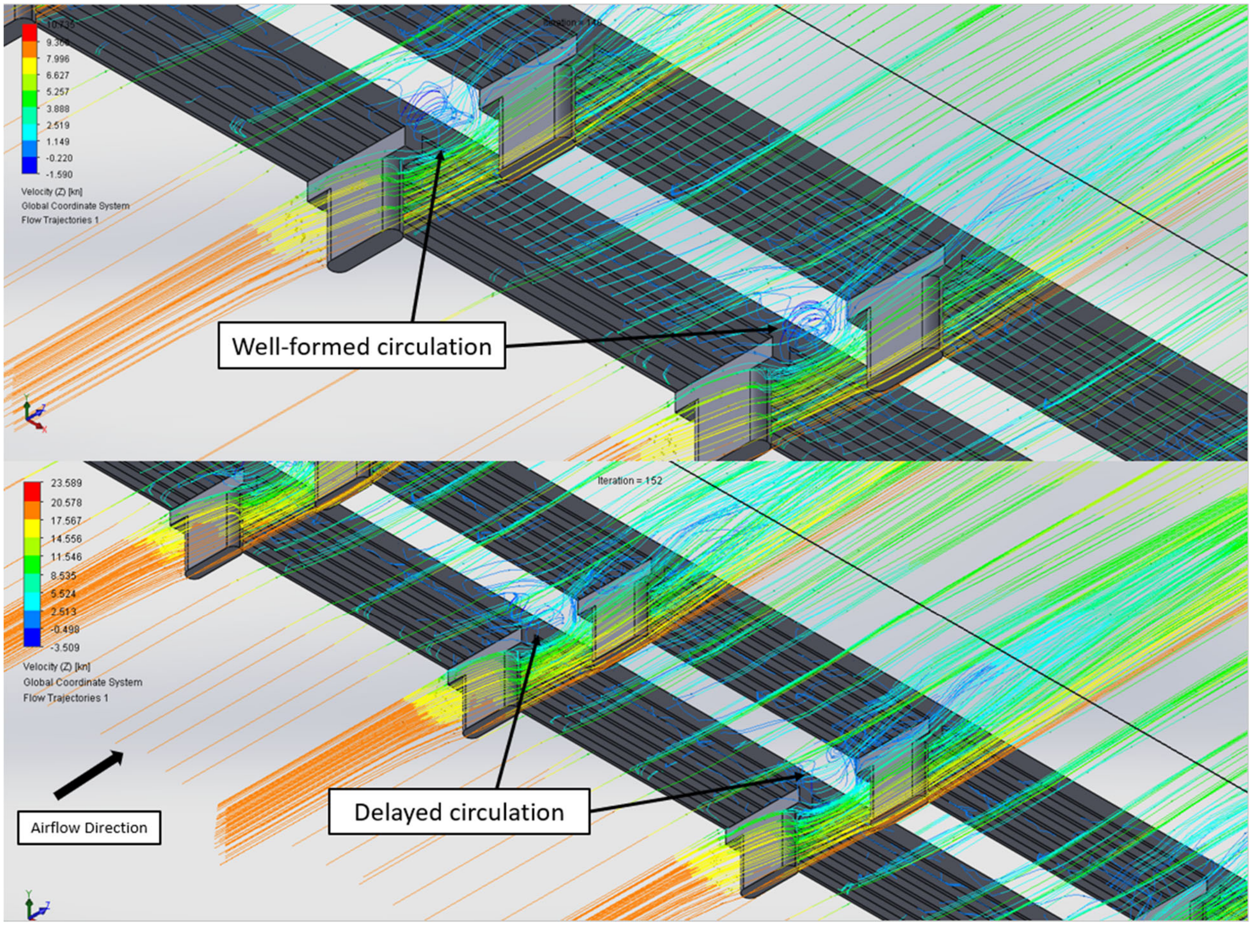

Figure 9. Pier-Induced Circulation between 9 knots (top) and 20 knots (bottom).

DISCUSSION

While the preliminary results discussed here indicate that areas of circulation and wind shear are common among bridges, this simulation model has limitations. CFD simulation technology has limitations based on the model created, of course, and not all real-world scenarios can be perfectly recreated computationally. For example, because bridge cross sections are relatively symmetric on a macro level, there are no drastic aerodynamic differences between the top and bottom surface when looking at the bridge deck exclusively. However, a difference is shown to arise when vehicles are present on the deck, as they tend to alter the airflow over the bridge. In addition to this, thermal convection created by higher temperature asphalt can cause the upward-moving air currents that pilots commonly experience; these can lead to instability of the aircraft. This may result in a greater turbulence effect on the top surface of the deck than on the bottom surface. It is possible, however, to determine commonalities that are at least somewhat predictable among most scenarios that may reasonably be expected to be encountered. The study results suggest that the turbulence phenomena described could be regularly associated with common bridge infrastructure, and hence, important for consideration with respect to inspection operations.

Possible Impacts and Future Work

The findings of this study suggest the potential for predicting areas of potentially hazardous UAS operation around bridge structures. These hazard zones are created as a result of interactions between ambient wind conditions and interactions of those winds with bridge structures. It is suggested that the existence of pier-induced circulation behind the piers and bridge deck may be found among many overpass bridge geometries. This could impact the areas in which a UAS-based inspection platform could safely operate. This also suggests the possibility of developing operational standards and a valid inspection plan for avoidance of hazardous areas once those areas can be identified. It is important that further research into the identification and forecasting of those hazardous areas for given sets of environmental conditions be continued.

APPENDIX A

Draft of Temperature Performance Test for Unmanned Aircraft Systems

The goal of this test is to evaluate performance of a UAS in different weather conditions artificially recreating them in an enclosed space.

General Provisions:

- *The UAS to be tested has to be fully charged and able to operate this test in its entirety without pauses or interruptions.*
- *Equipment has to be in the facility for at least 1 hours prior testing, unoperated and in an adequate room maintaining ambient conditions at the target test temperature.*
- *The chamber or room where the test is going to be performed has to meet these requirements:*
  - *Closed space without any other equipment apart from the ones contemplated on this test and the UAS.*

Specific Provisions for this test:

- *Per recommendation of the Department of Defense Test Method Standard: Environmental Engineering Considerations and Laboratory Tests, in order to prevent thermal shock, control the rate of temperature change to not exceed 3°C (5°F) per minute while bringing the UAS to the target temperature.*
- *Test chamber: an enclosed space, isolated from ambient or nearby conditions that could interfere with the test. The test operator has to be able to manipulate the temperature of this space according to test requirements. Examples of test chambers: commercial cooling chamber, insolated box, isolated room.*

Procedure:

1. *Place the equipment in the test chamber.*
2. *Set the chamber to the target temperature. If the humidity is to be controlled, it shall be set to 50% relative humidity. Allow relative humidity and equipment temperature to stabilize.*
3. *Power the equipment and allow it to reach the specified hovering position and begin streaming live video to the remote monitor.*
4. *Concurrently with step 3, begin timing the interval from the start of hovering and continue until the battery limit is reached.*
5. *Remove the equipment from the chamber, and inspect the UAS for signs of damage or change in condition of camera and parts.*
6. *The test shall be repeated three (3) times at each target temperature using three different batteries and all three flight times recorded along with the average.*