TECHBRIEF

Controlled-Environment Testing of UAS Digital Camera Sensor Specifications and Operational Parameters for Bridge Safety Inspections

FHWA Publication No.: FHWA-HRT-21-060

FHWA Contact: Hoda Azari, Nondestructive Evaluation Program and Laboratory Manager, HRDI-20, ORCID: 0000-002-7340-0035, 202-493-3064, hoda.azari@dot.gov

This document is one in a series of technical summaries that accompany the forthcoming Federal Highway Administration report *Collection of Data with Unmanned Aerial Systems (UAS) for Bridge Inspection and Construction Inspection.*

INTRODUCTION

As more bridge inspection programs incorporate unmanned aerial systems (UAS) as a tool to enhance the inspection process, fact-based information on optimum specifications for the sensors UAS can carry and other key operational considerations impacting UAS imagery will aid bridge owners and inspectors when considering the acquisition and operation of UAS. Research for this TechBrief and its companion report was conducted both in the field as well as in a laboratory setting to capture and analyze data that will assist agency decisionmakers when considering integrating UAS into their inspection programs.

This TechBrief discusses the testing conducted at the University of Maine to examine the key parameters that can be controlled or managed by the operator to positively impact the quality of UAS imagery. These parameters include the following sensor settings:

- Exposure, shutter speed, and ISO settings for sensor sensitivity to light.
- Aircraft navigation and stabilization.
- UAS standoff distance from the bridge structure.
- Wind speeds.
- Lighting.

This TechBrief offers recommendations to aid in both UAS acquisition and operational decisionmaking.

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

https://highways.dot.gov/research

BACKGROUND

An increasing number of bridge owners and bridge inspection service providers are integrating UAS as a tool for bridge inspections. This expanding use is a result of the growth in the technological capabilities of the aircraft and the sensors they carry combined with eased restrictions on using UAS by the Federal Aviation Administration. Early adopters over the last few years have discovered new ways to use UAS in bridge inspection processes and effective means to employ the systems in support of inspection tasks.

The use of UAS during bridge inspections can offer tangible benefits, key among which are enhanced safety and reduced inspection costs. At present, UAS cannot provide the full spectrum of "hands-on" capabilities available to an inspector; therefore, the tests conducted as part of this research effort focused on the capability of the UAS camera to provide usable data for supplementing traditional routine inspection techniques. What the UAS can provide is enhanced inspection findings from visual sensors to capture high-definition imagery of the bridge structure. To capture the best quality imagery using UAS sensors, the user can take advantage of both the system's capabilities as well as the pilot's operating practices as developed by early adopters of UAS for bridge inspections.

To provide operators in the field with recommendations they can use when selecting a UAS and to identify operational considerations that would optimize the quality of the imagery captured for inspection analysis and reporting purposes, research was performed both in the field and in a laboratory setting to test several operationally relevant parameters of these aircraft systems. The purpose of this TechBrief is to highlight the testing that took place in a controlled environment, explain how the results validated observations made during select bridge inspections performed in the field, and provide recommendations for inspectors planning to employ UAS.

The focus of this TechBrief is the controlled, laboratory-environment testing conducted by the research team at the facilities of the University of Maine in Orono from December 10–12, 2019. The team conducted UAS flight testing using three aircraft with different sensor systems to explore how sensor settings; aircraft motion, navigation, and stabilization; aircraft standoff distance and zoom capabilities; and available and augmented lighting conditions impact the quality of the inspection imagery. This TechBrief offers recommendations for the bridge owner and the UAS operator based on the results of this testing.

TESTING OBJECTIVES

The purpose of testing in a controlled-environment laboratory was to determine the operational specifications that a UAS and the optical sensor (typically a digital camera carried as a payload) need as a baseline to be used effectively in support of routine bridge safety inspections as well as the capability of the UAS to identify defects, such as cracks, for hands-on follow-up inspections. The primary objectives of the testing included determining the following:

- Minimum internal camera setting ranges and resolutions required to obtain usable images of bridge defects
- Minimum navigation systems for maneuvering in and around the structure and capturing accurate location data to geotag each image.
- Effective standoff distance from the bridge structure and whether the sensor's zoom capabilities can mitigate standoff ranges.
- Minimum levels of lighting required for adequate images.

SYSTEMS USED IN TESTING

The three optical sensors used during the tests had the following specifications:

- Sensor 1:
  - » Camera resolution: 21 megapixels (MP).
  - » Sensor type: 1⁄2.4-inch complementary metal-oxide semiconductor (CMOS).
  - » Aperture: f⁄2.4 (Fixed).
  - » Zoom: 2.8×, Digital.
  - » Shutter speed: 1–1⁄10,000th s.
  - » ISO range: 100–3,200 (video); 100–1,600 (image).
- Sensor 2:
  - » Camera resolution: 12 MP.
  - » Sensor type: 1⁄2.3-inch CMOS.
  - » Aperture: f⁄2.8–f⁄3.8.
  - » Zoom: Dynamic; 2× Optical, 3× Digital.
  - » Shutter speed: 8–1⁄8,000th s.
  - » ISO range: 100–3,200 (video); 100–3,200 (image).

- Sensor 3:
  - Camera resolution: 20.8 MP.
  - Sensor type: 4⁄3-inch CMOS.
  - Aperture: Variable.
  - Zoom: Fixed.
  - Shutter speed: 8–1⁄8,000th s.
  - ISO range: 100–6,400 (video); 100–25,600 (image).

These sensors were each associated with one of three separate aircraft platforms with varying flying and stabilization capabilities.

TESTING METHODOLOGY

Testing was conducted indoors in a Global Positioning System (GPS)-denied environment where lighting and wind conditions could be varied to simulate different field conditions. The UAS captured images of concrete samples with cracks as well as images of additional structural defects printed to scale to explore how internal camera settings, aircraft navigation and localization of the defects, aircraft distance from the defect, and lighting, including the use of external lighting, impacted the quality of the captured images. Each of these four areas were examined during the study by combining varying light intensities, wind speeds, aircraft stabilization systems (such as GPS and indoor navigation), and distances from the defect.

For example, a set of images was collected 5 ft away from the defect with a wind speed of 5 mph and at a lighting intensity of 1,000 lx. Varying sensor settings were applied to determine the effect, if any, that those specific conditions had on image quality. The parameters were varied and recorded for a broad number of combinations.

SENSOR SETTINGS

Two sensor settings were found to be the most influential on the quality of UAS-captured images: exposure and shutter speed.

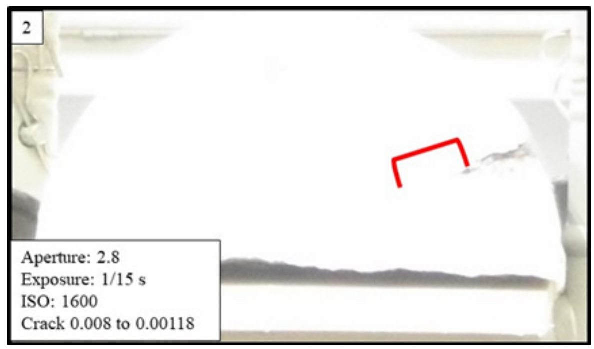
Exposure

Images were captured under various lighting conditions to determine the camera's ability to compensate for changing lighting conditions. The images shown in figure 1 were taken 5 ft from the defect, with a light intensity of approximately 1,100 lx, which is approximately equivalent to an overcast day. The three images show the same defect.

Figure 1. Photos. Compound figure showing exposure examples.

A. Example at 1⁄30th-s exposure.

B. Example at 1/15th-s exposure.



C. Example at 1/100th-s exposure.

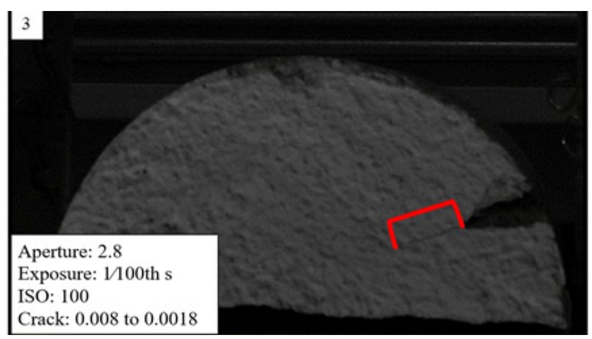


Figure 1-A is properly exposed and was taken using automatic settings. Figure 1-B is overexposed, and figure 1-C is underexposed; both were taken using manual adjustments to the exposure settings to provide comparisons with the other settings that were

Table 1. Camera settings for exposure testing.

Image	Aperature	Shutter S peed	ISO
1	2.8	1/30th s	120
2	2.8	1/15th s	1,600
3	2.8	1/100th s	100

automatically adjusted by the camera for the best image at a given shutter speed. The sensor settings for each image are displayed in table 1.

By exploring the exposure technology available in the cameras used for testing, the research team concluded that the best approach to obtaining high-quality, usable images was to allow the software to automatically calculate the proper settings. Using automatic settings not only resulted in higher-quality images, it also allowed the inspector to focus on inspecting the structure for defects rather than adjusting sensor settings.

Shutter Speed and ISO Setting

The shutter speed of the camera determines the amount time that the sensor element is exposed to light when the image is captured. For this test, a series of images was taken to show how the images were impacted by changing the shutter speed in concert with changes to the ISO setting, another key sensor setting that adjusts sensitivity to light. Images were taken 5 ft from the defect with a lighting intensity of 1,100 lx to simulate an overcast day. Shutter speeds of 1/15th, 1/30th, 1/50th, and 1/100th s were used, with the ISO settings varying within the 100 to 800 range at each shutter speed, resulting in 19 total images taken and compared.

In general, the images captured while manually adjusting the shutter speed and ISO tended to be grainy or blurry and were of little value for assessing the extent of the defect. However, the exception to this trend occurred was when the ISO and shutter speed were manually adjusted to within a range similar to that which the camera's automatic settings had calculated, as seen in figure 2 and figure 3.

The manual settings were matched as closely as possible to the automatic settings calculated by the camera. In this instance, unlike most of the other images taken with a manually adjusted camera, the image of the defect is slightly better defined. Thus, an inspector may find value in refining the image manually in certain situations, but the camera's automatic settings serve the operator more effectively as an initial setting.

Figure 2. Photo. Image of concrete defect taken with automatic settings.

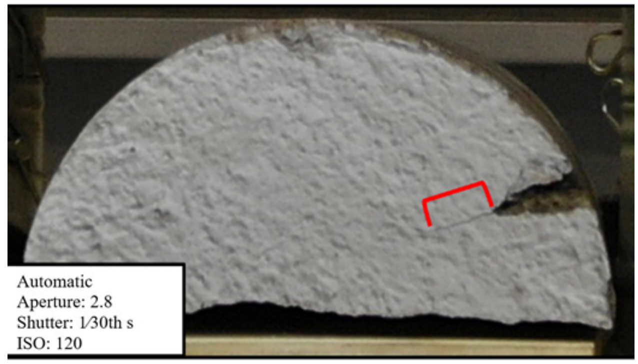
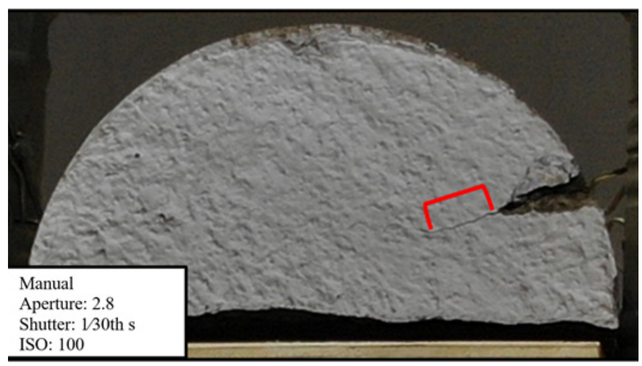


Figure 3. Photo. Image of concrete defect taken with manual settings.



NAVIGATION AND LOCALIZATION

The ability of the UAS to remain stable and safely navigate around the bridge structure most often relies upon GPS. GPS provides accurate information on location data (i.e., latitude, longitude, and altitude) as well as three-axis stabilization data for the aircraft's flight control system. If the GPS is unavailable (the typical condition when flying under a bridge deck) the system will become less stable in flight unless it has an alternate means of automatic stabilization. The UAS sensor in a GPS-denied environment also loses the ability to provide location data for the collected images. The loss of location data will not impact image quality but will create additional work during postprocessing.

STABILIZATION

During normal operations with a GPS signal available, the UAS will maintain its positions with a high degree of accuracy. However, when GPS is lost, as is likely to occur under the structure, aircraft stabilization is entirely dependent on the pilot's skill. Loss of the GPS signal requires the pilot to anticipate wind conditions and then direct the aircraft in a timely manner to avoid contact with the structure. Such continuous corrective movements can impact image quality.

The GPS-denied condition was tested on two different systems with indoor stabilization capabilities (i.e., systems capable of surveilling indoor, inaccessible, and confined spaces) to compare the inherent stability of those systems against a system that does not have indoor stabilization. The UAS equipped with stabilization systems sensed the change in the aircraft's location and automatically compensated for wind speeds up to 20 mph, holding the aircraft's position with minimal lateral or horizontal movement. However, the number of corrections the systems had to make to hold this position created significant motion blurring and impacted the pilot's ability to acquire usable images of the defects. Testing above 20 mph was not conducted for safety reasons.

The third system tested did not have indoor stabilization and was very unstable without GPS, requiring constant pilot input to maintain position with no external forces. When a 5 mph wind was generated, the system became unstable to the point that the number of pilot corrections required made the imagery collected unusable for assessing the defects. Testing the third system was not attempted with winds above 5 mph for safety reasons.

During field inspection testing, the two systems with indoor stabilization capability did experience intermittent loss of stabilization. While the cause remains undetermined, the research team postulated that it may have been due to the metal construction of the bridge or possibly because of power lines near the structure.

MOTION BLUR

A stable platform is very important for the image quality captured (figure 4-A). In the absence of a stable platform, the camera will have difficulty capturing a clear image. The blurring of an image due to aircraft motion (or motion blur) is typically a result of movement of the camera, an improper shutter speed, or a combination of both. Motion blur can also result from the aircraft not being able to stabilize due to winds exceeding UAS operating limits or a denied or unstable GPS signal without a secondary stabilization system, as was the case in figure 4-B.

Figure 4. Photos. Motion blur example.

A. Motion blur example with exposure at 1⁄30th s and ISO set to 400.

Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

B. Motion blur example with exposure at 1⁄8th s and ISO set to 800.

Original photo: © 2020 Marc Maguire. Sensor-captured photo of original: © 2020 VHB.

Multiple images of the bridge defect in figure 4 were captured from 10 ft away; however, approximately 50 percent of the images experienced motion blur at shutter speeds ranging from 1/8th to 1/40th s. The blurred images were attributed to the aircraft's instability due to the lack GPS stabilization and not being equipped with indoor stabilization capabilities.

STANDOFF REQUIREMENTS

Another important operational parameter when using a UAS to collect images of defects is standoff. Standoff refers to the distance between the UAS and the structure. Testing revealed that a standoff distance of 5 ft without zoom was sufficient to visualize and capture quality images of a bridge defect in most cases.

Standoff testing was accomplished in sustained winds of 15 mph with minimal effect on the quality of the images collected (figure 5-A through figure 5-C).

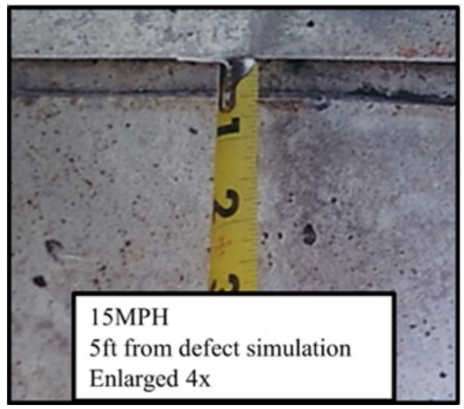
The tests did not account for the potential of wind gusts in the field environment because the research team was unable to simulate gusts well in the laboratory setting. Thus, caution should be used when attempting to capture bridge images at close range with a UAS in the field.

Of all the variables that could be accounted for in attempting to obtain the minimal standoff, the pilot is one of the most important and most subjective. The skill of the pilot should be a factor in determining standoff. During inspection flights in the field, the research team's UAS pilot (who was very experienced and highly skilled) was comfortably able to fly the aircraft approximately 3 ft from the bridge structure and felt that a pilot with average skills and experience could operate safely at that standoff range. Thus, the finding that a 5-ft standoff was sufficient to capture quality inspection imagery provides an added safety margin; however, it may be necessary to move closer to the structure to capture some defects. To offset the potential lack of a skilled pilot or marginal wind conditions, companies are now manufacturing drone propeller cages that enclose the entire propeller to protect it from accidental contact with objects that could potentially damage the UAS. While not used during these tests, these cages may provide an extra layer of protection.

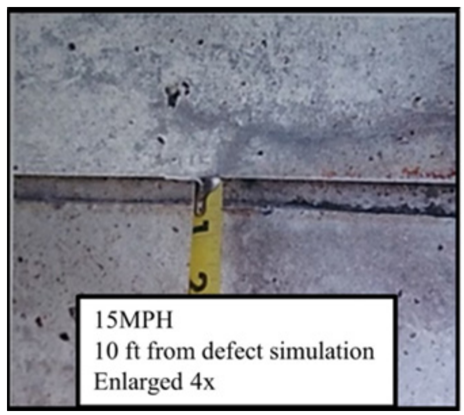
Another important factor in determining standoff distance is the experience of the inspector and how comfortable they are with the visibility of the details in the images. The inspector will be the final judge as to whether images are usable, but the standoff distance must account for the experience and comfort levels of both the inspector and the pilot.

Figure 5. Photos. Image quality comparison at varying standoff distances.

A. Photo taken 5 ft from defect simulation.



B. Photo taken 10 ft from defect simulation.



C. Photo taken 15 ft from defect simulation.

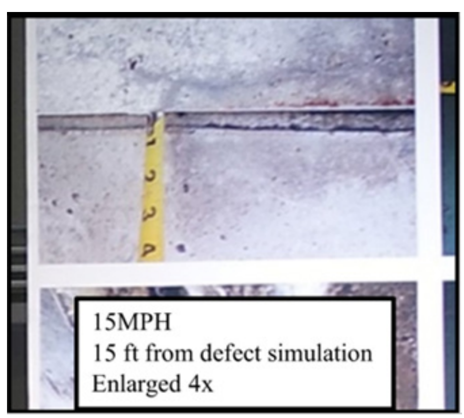
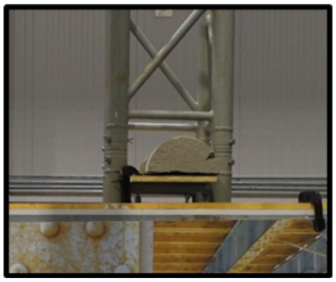
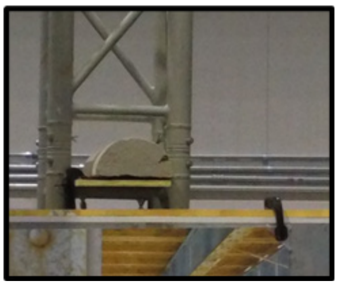


Figure 6. Photos. Zoom comparison at 5 and 15 ft.

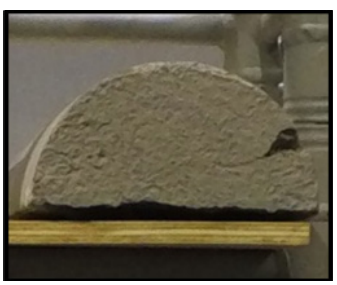
A. Photo from 5 ft with 0× zoom.



B. Photo from 15 ft with 3× zoom.



C. Photo from 5 ft with 0× zoom, magnified 4×.



D. Photo from 15 ft with 3× zoom, magnified 4×.

DISTANCE VERSUS ZOOM

In certain situations, the conditions around the bridge might preclude flying the UAS within 5 ft of certain parts of the structure. The standoff distance can be increased if the UAS being used has a zoom capability, preferably an optical zoom so no data are lost through pixelation. When zooming, there is a potential tradeoff in image resolution. Thus, the research team sought to determine whether zooming in from a greater standoff would degrade image quality.

The effect of zoom on an image was tested at varying distances to produce an image equivalent to one being taken within 5 ft of the structure. Determining these equivalent distances was accomplished by capturing images at 5, 10, and 15 ft without zoom and then with maximum zoom. Figure 6 shows representative examples of images taken using varied zoom powers and illustrates variations in image quality when enlarged during postprocessing.

Figure 6-A was taken from 5 ft without magnification, and figure 6-B was taken from 15 ft with 3× zoom. These original images look very similar. However, the difference in resolution can be seen when the image undergoes postprocessing enlargement and cropping. The images in figure 6-C and figure 6-D show the same defect enlarged four times from its original size. As can be seen, a lower level of zoom from a closer range produces visibly better results (figure 6-C) than a zoomed image. This difference in image quality should be taken into consideration should zooming be necessary for flight safety.

LIGHTING REQUIREMENTS

Even on a clear, sunny day, the undersides of bridge decks may have reduced lighting conditions. Testing was conducted to examine the requirements necessary to capture inspection-worthy images when external lighting, or UAS lighting attachments, is used to improve image quality.

Because lighting conditions in the intensity ranges that an inspection team would experience on a sunny day were unattainable in the lab, three different lighting conditions were used to simulate levels of light that could be experienced outside under cloudy conditions. These conditions included medium or mostly cloudy (1,500–5,000 lx), overcast (1,500–100 lx), and dark, such as near dawn or dusk (100–0 lx). To ensure consistency, all light measurements were tracked at the center of the defect images with a light meter that measured from 0–100,000 lx.

As might be expected, lighting intensities less than 100 lx presented the biggest challenge for collecting usable imagery. Images at those lighting levels were generally grainy and lacked detail, even when taken from 5 ft away without any zoom. With lighting more than 100 lx, however, the automatic settings for the cameras provided inspection-quality images.

EXTERNAL LIGHTING

In some instances, the available light under a bridge will be insufficient to adequately capture inspection-quality images. Overcoming poor lighting conditions can be achieved by using external lighting, a capability available with some UAS models.

A test was conducted with a UAS capable of carrying an external lighting attachment that provided 50,000 lx at 3 ft; 5,000 lx at 5 ft; and 11 lx at approximately 100 ft.

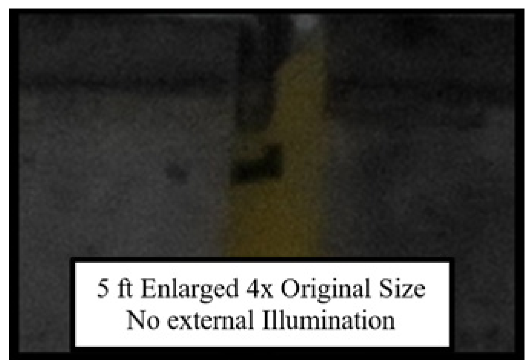
The images in figure 7 were taken with and without external lighting at distances of 5 and 15 ft. The images show the difference between using the external light source (figure 7-A) and the available lighting (figure 7-B). At such close range, external light adds a great deal to the quality and usability of the image.

The image in figure 7-C was taken from 15 ft using the external lighting source, while figure 7-D was taken with available light. A close look at figure 7-C shows that using the external light source from 15 ft away does add a bit of clarity to the image as compared to figure 7-D, but the difference is almost imperceptible. Thus, when needed, external lighting carried by the UAS can improve the image quality when used at a close range; however, based on testing parameters and the external lighting capability of 5,000 lx at 5 ft and 11 lx at approximately 100 ft, external lighting does not offer a significant improvement to image quality beyond 15 ft.

Figure 7. Photos. External lighting: postprocessed image comparison.

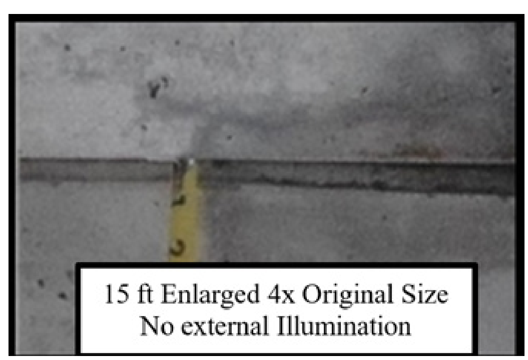
A. Example from 5 ft, enlarged 4× original size, with external illumination.

B. Example from 5 ft, enlarged 4× original size, with no external illumination.



C. Example from 15 ft, enlarged 4× original size, with external illumination.

D. Example from 15 ft, enlarged 4× original size, with no external illumination.



UAS SPEED FOR DEFECT DETECTION

An additional parameter considered for testing was the maximum velocity at which the UAS could travel while still providing image quality sufficient to detect defects. Due to time constraints and lack of defect surfaces in the laboratory environment, this testing was not practical to perform. However, other studies have attempted to capture the best speed for detection. The Oregon Department of Transportation (ODOT) is one of the organizations studying this parameter. The ODOT research team concluded that the optimal speed for defect detection was less than 3 ft/s when the UAS was flown in a manner that was consistent with the perspective an inspector would have if using an under-bridge-inspection truck or climbing the bridge structure. (Gillins et al. 2018) Higher rates of speed can be used when the UAS is flying further away and high levels of detail are not required, such as during mapping.

This finding is consistent with what has been observed during data collection in the field. In general, slower is better, and stationary is best when flying near the bridge to obtain high levels of detail in the images. Each inspection scenario will have different variables, and each must be considered. The best speed at which to detect defects will have be determined on site by the inspector based on their experience and objective analysis of the imagery being provided by the UAS.

RECOMMENDATIONS

Based upon the results of the laboratory tests, the research team determined the following recommended minimum sensor features and operating limitations to ensure usable data when employing UAS to support bridge safety inspections:

- Sensor resolution. The camera should have an inherent ability to produce quality images. The minimum megapixel count should be 12 or more. Nearly all UAS sensors available today have a resolution of at least 12 MP. Technology advances will only improve upon the minimum camera resolution available.
- Sensor settings. Testing found that the most effective and practical mode for sensor operation is using the automatic settings. The highest image quality should be obtainable using automatic sensor settings in most scenarios, so the user should not be required to manipulate the camera settings manually to collect usable images. Using automatic settings will allow the inspector to focus on assessing the defects. If the inspector is also the pilot, it will reduce the number of tasks an individual is responsible for, thus improving flight safety and shortening the time needed for postprocessing by reducing the number of corrections that need to be made to the images. In terms of lighting, the camera at minimum should be able to sense available light conditions automatically and adjust its settings accordingly. However, based on the settings that were tested and the results of those tests, the camera should also offer users the ability to manually adjust the ISO setting from 100 to 3,200 and to manually change the shutter-speed setting, which controls exposure, from 1/15th to 1/100th s. Users should keep in mind that manual manipulation of these settings has an increased probability of capturing a poor-quality image (i.e., one that is blurry, grainy, or both).
- Standoff distance. Maintaining a standoff distance of 5 ft or more with an optical zoom capability will produce inspection-quality images and reduce the likelihood of the aircraft colliding with the structure. Standoff becomes especially important when the system used does not have indoor stabilization to back up the GPS. In GPS-denied environments where winds exceed about 5 mph, UAS can experience movement of several feet. This movement requires that the pilot be vigilant and prepared to make stabilizing corrections to the aircraft. Lack of stability can jeopardize flight safety when operating at standoff ranges of 5 ft or closer and can also cause blurring in the images, making them inadequate for assessing defects. These factors can largely be negated by using a system with an indoor stabilization capability as a backup for GPS stabilization.
- Wind conditions. Wind speeds of more than 15 mph generally degrade the stability of the UAS and thus the quality of the imagery so much that it is not usable for inspection purposes. Wind conditions and the ability to fly and image effectively must be determined locally at the inspection site prior to takeoff, and the inspection team should consider how the UAS will be operated (i.e., either with one control or a dual control setup). While the use of one controller is not the optimal control configuration, if one controller is used with the inspector acting as the pilot and flying the UAS while evaluating the defects, then the operating minimums should account for the increased risk of UAS damage and lower quality images as the inspector will be dividing their attention. Pilot experience is a key consideration in high-wind conditions. During the testing conducted for this study, a skilled and experienced pilot operated the UAS. Nonetheless, the pilot had trouble maintaining stability in turbulent winds at

15 mph or more. Winds of 15 mph or more also created significant difficulty in capturing usable imagery due to the frequent attitude corrections that the pilot and the stabilization system had to make to keep the aircraft in its relative position.

- Zoom versus distance. UAS with optical zoom, while not necessarily a requirement, will provide a more detailed image of a defect area while in flight as well as give the pilot the ability to maintain a greater standoff distance from the structure. While zoom capabilities can be a valuable aid to the inspector when identifying defects, using optical zoom (particularly above 3× zoom) will negatively impact the resolution of the captured imagery during postprocessing should the imagery require enlarging. However, evaluating defects using the camera while in flight can be difficult at times due to the resolution of the monitor; thus, the ability to zoom in can be an advantage for the inspector operationally.
- Available lighting. The intensity of lighting proved to have minimal effect on imagery outside of the conditions that would be experienced under a bridge deck or other conditions of low light. Most often the camera's automatic setting adjustments will provide a usable image, but there may be times that settings must be adjusted manually.
- Augmented lighting. The use of external lighting can improve image quality in low-light conditions. Manual adjustment of camera settings tends to adversely affect image quality, often making the images grainy or blurry due to the motion of the UAS. Using external lighting can sufficiently light the foreground, allowing the camera's automatic setting adjustments to capture the highest quality image without affecting the overall image quality, particularly at ranges around the recommended standoff distance of 5 ft. In general, the maximum standoff for external lighting to be effective was approximately 15 ft for tested luminance. However, this distance is subject to both the defect that is being examined and the judgment of the inspector as to whether the lighting in a given scenario is sufficient to create a usable image of the defect.

REFERENCES

1. Gillins, Daniel T., Parrish, Christopher, Gillins, Matthew N., and Simpson, Chase. 2018. Eyes in the Sky: Bridge Inspections with Unmanned Aerial Vehicles, Report No. FHWA-OR-RD-18-11, Oregon Dept. of Transportation, Salem, OR, and Federal Highway Administration, Washington, DC.

Researchers—This research was conducted by Futron Aviation Corporation with support from Vanasse Hangen Brustlin, Inc., under contract DTFH61-17-R-00036.

Distribution—This TechBrief is being distributed according to a standard distribution.

Availability—This TechBrief may be obtained from http://www.fhwa.dot.gov/research.

Key Words—Bridges, post-tensioning, grout, chlorides, corrosion, fracture, inspection, sampling, repair.

JUNE 2021

Recommended citation: Federal Highway Administration, Controlled-Environment Testing of UAS Digital Camera Sensor Specifications and Operational Parameters for Bridge Safety Inspections (Washington, DC: 2021) https://doi.org/10.21949/1521636.

FHWA-HRT-21-060
HRDI-20/06-21(WEB)E