

**Use of sUAS in Developing  
Photogrammetric Model for Wind Simulation**

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Presented to:

International Society of Air Safety Investigators (ISASI)

ISASI 2018 Seminar Dubai

“The Future of Aircraft Accident Investigation”

Authors' note:

This white paper is not intended to be a scientific study.

The activities conducted served as a proof-of-concept for an innovative investigative technique, demonstrating the breadth of potential use cases for sUAS to support accident investigation.

## Abstract

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During the on-scene investigation of an accident involving a runway overrun of a transport-category airplane, NTSB investigators discovered that the airplane’s right elevator’s geared tab linkage components were locked in an overcentered position and bent outboard, effectively jamming the right elevator. Although investigators suspected the condition may have resulted from the airplane’s exposure to high, gusting winds while parked on the ramp before the flight, a lack of local wind data availability due to equipment power outages, as well as the likely effects of a large hangar on the wind characteristics where the airplane had been parked, challenged the investigation’s ability to explore the possible wind-damage scenario.

The NTSB meteorologist assigned to the investigation determined that a computational fluid dynamics (CFD) simulation of the wind flow around the hangar would provide insight into the types of gust loads that may have affected the airplane. Boeing, a party to the investigation, could perform the simulation but needed a three-dimensional (3D) digital model of the hangar to

import into its CFD software. However, because the hangar was built in the 1940s, conventional methods to model it would require the use of blueprints, photographs, and terrain data sources to manually create the structure using computer-aided design software. Given the size and complexity of the building and the surrounding terrain, such an effort would involve considerable time and manpower and may not produce the model accuracy needed for use in a CFD simulation.

To explore the possibility that an accurate 3D model of the hangar could be created more quickly and efficiently, the NTSB's Unmanned Aircraft System (UAS) Team evaluated, planned, and conducted a multi-sortie flight mission using a small UAS (sUAS, or drone) on an operating airport in controlled airspace to acquire the imagery needed for photogrammetry processing. Although the NTSB UAS Team had been using drones as a new investigative technique for capturing imagery at various accident sites for about 1 year, supporting the development of a 3D model for use in a CFD wind simulation was a new application of this technology.

The team used commercially available photogrammetry software to process the drone-captured imagery, which resulted in an accurate 3D model that Boeing successfully used in the CFD wind simulation. The use of an sUAS in this capacity resulted in a superior product that was developed in a much more timely and cost-effective manner than traditional methods. Collectively, these efforts assisted the NTSB airplane systems group chairman and the systems investigative group in developing and refining static and dynamic load test cases for the airplane's elevator control system, which were essential for analyzing possible wind-damage scenarios.

As a side benefit, the NTSB UAS Team's drone-captured imagery and 3D model of the hangar, which was historically significant but scheduled for demolition, preserved a piece of history in a digital format. Known as Hangar 1, it was one of the last standing buildings of the former assembly factory for the Consolidated B-24 Liberator bomber from World War II.

*Keywords:* sUAS, drone, 3D model, Pix4D, aircraft accident, wind, meteorology, CFD, photogrammetry

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## Abbreviations

3D	three-dimensional
agl	above ground level
AMM	aircraft maintenance manual
ASOS	Automated Surface Observing System
ATCT	air traffic control tower
ATIS	Automatic Terminal Information Service
Boeing	The Boeing Company
CAD	computer-aided design
CFD	computational fluid dynamics
<i>CFR</i>	<i>Code of Federal Regulations</i>
cm	centimeter
CMOS	complementary metal-oxide semiconductor
COA	Certificate of Waiver or Authorization
CORS	Continuously Operating Reference Station
DGPS	differential global positioning system
eCOA	emergency Certificate of Waiver or Authorization
FAA	Federal Aviation Administration
FBO	fixed-base operator
FDR	flight data recorder
ft	feet
GCP	ground control point
GIS	geographic information system
GPS	global positioning system
GPU	graphics processing unit
GSD	ground sample distance
in	inch
km	kilometer
kts	knots
LAANC	Low Altitude Authorization and Notification Capability
m	meter
mp	megapixel

m/s	meters per second
MSP	Michigan State Police
NOTAM	Notice to Airmen
NTSB	National Transportation Safety Board
RPIC	remote pilot in command
SAWS	Stand Alone Weather Sensor
SGI	Special Government Interest
sUAS	small unmanned aircraft system
TED	trailing edge down
TEU	trailing edge up
UAS	unmanned aircraft system
VLOS	visual line of sight
VO	visual observer
WWII	World War II
YIP	Willow Run Airport

## **Introduction**

During the on-scene investigation of an accident involving a runway overrun of a transport-category airplane, National Transportation Safety Board (NTSB) investigators discovered that the inboard linkage components of the right elevator's geared tab were locked in an overcentered position and bent outboard, effectively jamming the right elevator. This condition prevented the right elevator from responding to cockpit control inputs and precluded airplane pitch response and rotation during takeoff (NTSB 2017c 10-11, 19; NTSB 2017d 17-21). Initial stages of the investigation found no evidence to suggest that the condition resulted from improper maintenance or collision with a vehicle or other object (NTSB 2017d 17, 21-30, 36-37). Before the accident flight, the airplane had been parked during a period of abnormally high, gusting wind conditions, and flight data recorder (FDR) information (which recorded when the right elevator was last in a different position) showed that the right elevator became jammed sometime during the 2 days that the airplane was parked on the ramp before the accident.

### **Statement of the Problem**

A lack of local wind data availability and the likely effects of a large hangar on the wind characteristics where the airplane had been parked challenged the investigation's ability to determine how the right elevator's geared tab linkage became locked overcenter. Although a computational fluid dynamics (CFD) wind simulation could provide insight into the likely characteristics of the windflow at the airplane's parked location, an accurate three-dimensional (3D) model of the large hangar upwind of the parking ramp was needed but could not be feasibly produced using conventional techniques. The windflow information was critical for supporting

the investigation's development of a series of static and dynamic elevator load tests to determine what conditions, consistent with the known circumstances of the accident, could result in the jammed elevator condition. Although the NTSB's unmanned aircraft system (UAS) Team had been using a fleet of small UAS (sUAS, or drones) as a new investigative technique for capturing imagery at various accident sites for about 1 year, supporting the development of a 3D model for use in a CFD wind simulation was a new application of this technology.

### Incomplete Meteorological Data for Airport

The accident occurred March 8, 2017, at Willow Run Airport (YIP), in Ypsilanti, Michigan, and an NTSB meteorologist was assigned to the investigation (2). Official wind observations at YIP were taken from an Automated Surface Observing System (ASOS) anemometer located near midfield, 1,490 meters (m) (4,888 feet [ft]) east of the location where the airplane was parked (NTSB 2017d 7, 10.) (See figure 1 [NTSB 2017b, 14].) This anemometer was at a height of 10 m (33 ft) above ground level (agl) and was sited to observe unobstructed wind flow from any direction. Although the ASOS is an authoritative source of wind data, due to a regional power outage, the ASOS anemometer became inoperative about 4 hours before (and remained inoperative until well after) the time of the accident (NTSB 2017b 7). Prior to the power loss, the ASOS anemometer's maximum observed wind gust (5-second average) was 55 kts from the west-southwest. ASOS anemometer data did not distinguish between the horizontal and vertical components of the wind.

Although two additional anemometers were present at YIP, neither provided investigators with authoritative wind data for the accident day. A Stand Alone Weather Sensor (SAWS) that included an anemometer was on the field northeast of the airplane's parked location; however,

the SAWS became inoperative about the same time as the ASOS anemometer, and archived data from before the power outage were not available (NTSB 2017b 12). Although another anemometer (which was owned by the local airport authority and located southeast of the airplane's parked location) continued to provide data even after the ASOS and SAWS lost power, a comparison of this anemometer's data with the ASOS data (for times when the ASOS was operational) revealed that the airport authority's anemometer's data showed a significant bias (NTSB 2017b 11-12). Further, the airport authority's anemometer provided data only every 5 minutes with some unknown sampling criteria, was at a height of about 2.7 to 3.1 m (9 to 10 ft), may not have been well-sited, and had unknown maintenance standards. The issues associated with these two anemometers, combined with the power loss to the ASOS, left investigators without credible wind information for YIP for about a 4-hour period before the accident (NTSB 2017b 8-12, 19).



Figure 1. Airport map showing the relative locations of the hangar (dimensions highlighted in red), the accident airplane’s parking spot, and various weather observing equipment.

Potential Effect of Large Hangar on Wind Flow

Although the ASOS anemometer provided reliable, authoritative airport wind information while it was operative, the airplane had been parked facing north immediately downwind from (on the east side) of a large hangar. The hangar was more than 0.4 kilometer (km) (0.25-mile) long and equipped with duct work, chimneys, ladders, and detailed architecture; it was also surrounded by bushes, trees, and varied terrain near a retention pond. All of these characteristics would likely disrupt windflow. Due to the size and characteristics of the hangar obstruction and surrounding terrain, as well as the distance of the airplane’s parked location from the ASOS, investigators suspected that any available airport wind data from the ASOS likely did not represent the localized airflow at the airplane’s parked location. (See figure 2 [NTSB 2017d 66].)



Figure 2. View looking west toward the hangar, taken from the approximate parked location of the accident airplane. (Airplane in picture is much closer to the hangar).

### **Need for Computational Fluid Dynamics (CFD) Wind Simulation**

Given the lack of complete wind data for YIP in the hours before the accident and the size and characteristics of the large hangar upwind of the airplane's parked location, determining the localized airflow that likely affected the airplane required an additional investigative technique. The Boeing Company (Boeing), which was a party to the NTSB's investigation, was capable of performing a computational fluid dynamics (CFD) wind simulation of conditions downwind of hangar using available wind data, pavement temperature information from an airport authority

sensor, and additional meteorological data (3). However, to maximize the fidelity of the wind simulation, a photogrammetric three-dimensional (3D) model of the hangar that could be imported into the CFD simulation was needed.

### **Limitations of Traditional Investigative Techniques for Developing Three-Dimensional (3D) Hangar Model**

Due to the 1940s vintage of the hangar, the likelihood of digital 3D model of it already existing -- especially with the fidelity necessary for the CFD work -- was remote. Creating a 3D model of the complex building and terrain environment would conventionally require using blueprints, photographs, terrain data, and computer-aided design (CAD) software to manually create the model. This would involve considerable resources in time and manpower. For example, it would be difficult to manually create the basic hangar structure alone, and adding the intricate accessories (duct work, chimneys, ladders, detailed architecture, bushes, trees, terrain near the retention pond, et cetera) could take weeks of additional labor. Further, such a monumental effort still may not provide the level of accuracy needed. For effective use in the CFD simulation, which has 0.5 m (1.6 ft) resolution, the input model must have at least that level of accuracy to model small-scale turbulent wind patterns caused by the obstructions.

### **Basis for Considering Use of sUAS as New Investigative Technique**

The NTSB meteorologist and NTSB systems investigator assigned to the investigation approached the NTSB unmanned aircraft system (UAS) Team Program Lead to determine the feasibility of using the NTSB's small UAS (sUAS) fleet to capture the necessary imagery and use it to create a photogrammetric 3D model of the hangar (4). At the time, the NTSB UAS Team had been using drones for about 1 year to capture imagery at various accident sites and had been

using the commercially available photogrammetry software to develop 3D models of the sites from the drone-captured imagery. Past models developed using the software were well within the accuracy requirements specified to support the CFD simulation for this investigation.

# Chapter 1

## New Investigative Technique

### 1.1 Evaluating Feasibility of Using sUAS Imagery to Develop 3D Model

#### 1.1.1 Determining Photogrammetry Product Compatibility

Before accepting the mission, the NTSB UAS Team needed to determine if the output products from a photogrammetry program could be imported into the CFD program used by Boeing. Photogrammetry, or more specifically, stereo photogrammetry, determines the 3D coordinates of points on an object by employing measurements made from multiple photographic images taken from different positions. Common points are identified on each image, and the intersection of the lines from the camera locations to the point on the object determines the 3D location. This 3D point cloud model of the subject is then used to build a textured mesh representation of the object. Although not as precise as the point cloud, the mesh object could potentially be used as a solid object in various software environments, such as the CFD wind simulation, and provide more detail than the simple geometric shapes normally used.

To capture imagery and create a mesh representation of an object that could be tested with the CFD software, the NTSB UAS Team conducted proving flights at the test facility near the NTSB Training Center in Ashburn, Virginia. (This “test track” was the former George Washington University solar vehicle field, which NTSB can use under agreement for UAS training and research and development.)

During one proving flight, the UAS Team thoroughly captured images of an equipment shed at the field using flight patterns recommended by Pix4D, the developer of the commercially

available photogrammetry software. The drone was flown in a double grid pattern with the camera pointed in combinations of nadir (straight down) and slightly off-vertical, as well as oblique patterns around the perimeter of the shed. The flight resulted in about 70 photographs, which were processed into a point cloud, and a 3D mesh in .obj format was exported for use in the CFD simulation model. (A .obj file is a geometry definition file. It is an open format and was developed by Wavefront Technologies for its animation software. The format is also used by various other 3D graphics applications.) The Boeing CFD specialist was able to import the test item into the CFD simulation model and, based on the results, was optimistic that such 3D mesh objects could contribute greatly to the accuracy of the model environment.

#### 1.1.2 Assessing Size of Structure and Area to be Modeled

Once the initial feasibility of providing a CFD-compatible model was demonstrated, the Boeing CFD specialist provided the UAS Team with specifications for the area to be modeled to support the wind simulation study. Conceptually, modeling the hangar was feasible for the UAS Team; however, at more than 0.4 km (0.25-mile) long, the structure was much larger than anything the team had modeled before. In addition, CFD specialist requested mapping of a large area of the surrounding terrain.

A map of the area of interest to be modeled was provided, with the highest priority being the southern portion of the hangar, parking ramp, and a nearby retention pond, with some lower priority “reach” areas across a vehicle lot. Although the CFD specialist initially requested a model of about only half of the hangar, the historical aspects of the hangar, which was scheduled for demolition, were considered. Known as Hangar 1, it was one of the last standing buildings of the former Willow Run Bomber Plant complex that produced the Consolidated B-24 Liberator

bomber from World War II (WWII) (Save 2018a). The UAS Team determined that acquiring the imagery to model the entire hangar would not require substantially more flight time. Thus, the UAS Team determined that mapping the entire hangar, thereby preserving it in a digital format, would be worth the additional effort. (See section 1.4 for more information.) Further, the additional imagery would be available to the investigation, if required for the analysis.

## **1.2 Conducting sUAS Flight Mission**

### 1.2.1 Preflight Planning to Capture Optimal Imagery

Considering the scope of the planned project, the NTSB UAS Team worked with specialists from the photogrammetry software company (Pix4D) to ensure that the planned missions would be flown a manner that most effectively and efficiently gathered the necessary data. The UAS Team developed a flight plan that incorporated double grids over the top of the entire hangar, followed by two orbits at different altitudes and camera angles to ensure full coverage of the sides of the building (NTSB 2017a). The altitudes of the grids and oblique flight paths were planned to give the best balance of coverage (including overlap) and accuracy. Grids flown at a higher altitude provided better overlap and matching between the photographs for the photogrammetry processing, especially considering the somewhat homogenous nature of the hangar roof. In a general sense, however, some photographic detail is lost with higher altitude because the ground sample distance (GSD) increases as the camera moves further from the ground. (In a digital photograph, GSD is the ground distance represented by the distance between the centers of two pixels.)

The UAS Team flew the hangar grids at 46 m (150 ft) agl and positioned the oblique flights to fill the frame to the extent possible with the target object (hangar) and minimize the

background, such as sky and ramp. The team positioned additional grids over the terrain and a small hangar to the south and east of the main hangar (see figure 3 [NTSB 2017a, 4]). Pre-planning the flight missions resulted in an estimate of more than 1 hour of expected flying and more than 1,000 images.



Figure 3. Orthomosaic image showing planned sUAS mapping area in yellow.

### 1.2.2 Airspace Access Considerations

At the time of the flights, gaining approval for conducting sUAS operations in controlled airspace (like YIP) involved either a time-consuming manual authorization process under Title 14 *Code of Federal Regulations (CFR)* Part 107 or the use of a government agency public safety emergency Certificate of Waiver or Authorization (eCOA). Initially, the UAS Team coordinated with the Michigan State Police (MSP) to ascertain if the MSP’s jurisdictional Certificate of Waiver or Authorization (COA), which covered the airport, could be used. (MSP officers were among the first responders to the accident and used their sUAS to photograph the wreckage,

ground scars, and runway.) Meanwhile, the NTSB UAS Program Lead began coordinating with the Federal Aviation Administration (FAA) for airspace access. During this process, the UAS Team learned that the MSP was unavailable at the proposed times for the flight; thus, an eCOA was needed. (Note: Currently, the FAA provides an automated airspace access system, Low Altitude Authorization and Notification Capability [LAANC], as well as the Special Government Interest [SGI] protocol, both of which allow for much more expeditious sUAS access to controlled airspace.)

The NTSB UAS Team had previously used eCOAs for conducting sUAS operations over active accident scenes, but none of those site areas had been as large as the hangar mapping project, which required lengthy flights in close proximity to manned aircraft operations. YIP was a busy freight hub in Class D airspace, underlying a shelf of the Detroit Class B airspace (see figure 4).

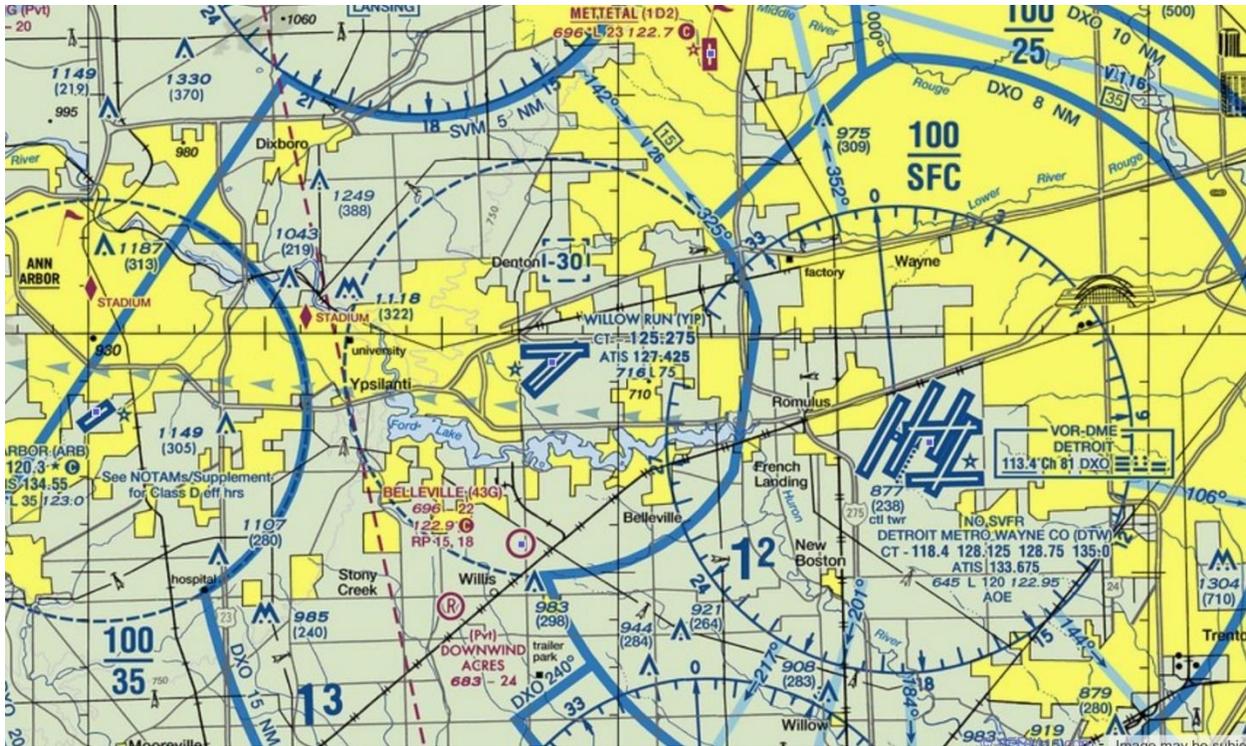


Figure 4. Sectional showing YIP and the surrounding the airspace.

Further, the hangar was located in between the ends of the two main runways and contained the U.S. Customs facility, a fixed-base operator (FBO), and other businesses. An active general aviation flight school was immediately south of (and sharing ramp space with) the hangar. The sUAS flights would need to operate concurrently with manned aircraft flights as the airport continued normal operations throughout the mission.

Fortunately, with excellent FAA cooperation, the eCOA was developed and issued with ample lead time before the mission. The NTSB UAS Program Lead provided a detailed map of the operating area and proposed flight plans (see figure 5), and FAA headquarters personnel coordinated with YIP air traffic control (ATCT) personnel to develop procedures for the flights. These combined efforts determined that operations under the eCOA were subject to the following requirements:

- A flight team consisting of a remote pilot-in-command (RPIC) and visual observer (VO),
- Issuance of a Notice to Airmen (NOTAM) prior to the day's sUAS flights (as coordinated between the FAA and NTSB UAS Program Lead).
- Restrictions that sUAS operations must remain clear of all runways and moving aircraft, and
- RPIC communication with the ATC tower personnel via two-way radio prior to each sortie.

The eCOA covered the planned mission date and included a contingency day to account for weather or data quality/operational issues, if needed.



Figure 5. eCOA showing the authorized sUAS operations area and altitudes.

### 1.2.3 Mission Considerations: Weather, Airport Activity, and Other Challenges

#### *Weather*

The mission day dawned with high, thin overcast and light surface winds, which were ideal for photogrammetric flights. However, the forecast called for storms to move through by the middle of the day, leaving a relatively narrow time window to accomplish the flights. In consideration of the approaching weather, the UAS Team prioritized the sorties to ensure the most critical portions of the hangar were captured first, in the event that subsequent sorties would have to be canceled.

#### *Preflight Coordination*

The UAS team, consisting of an RPIC and VO, arrived early to the hangar and contacted the ATCT personnel, who acknowledged the NOTAM information and added an advisory on the Automatic Terminal Information Service (ATIS) to advise local pilots of the UAS activity near the hangar below 61 m (200 ft) agl. Airport management was supportive, providing access to the airside ramp east of the hangar and the area around the flight school hangar.

#### *Mission Sorties*

The UAS Team staged the drone for the first sortie at the northwest corner of the hangar. Per the established plan, the first overflight grid was flown at 46 m (150 ft) agl. Breaking up the grid into four separate flights (one for each quadrant) aided in maintaining required visual line of sight (VLOS) with the drone and provided the opportunity for the team to quality check the image files (as described below) while the drone was landed between flights.

To maximize efficiency, the RPIC and VO worked a rotating plan of action: While the RPIC (UAS Program Lead) input the flight plan grids or orbits on the sUAS control tablet, the VO used a differential global positioning system (DGPS) to survey ground control points (GCPs) around the hangar. After each sortie, while the RPIC swapped out drone batteries and prepared for the next mission, the VO downloaded the images from drone's data card, reviewed them, and created backup copies of the images.

As the missions proceeded, the team decided to fly an extra orbit around a small tower to ensure the best detail coverage of the complex structure and angles, which might affect the wind simulation. While orbiting the small tower, which housed radio equipment for the U.S. Customs and FBO operations, the RPIC experienced a brief global positioning system (GPS) and compass error with the sUAS. To address the issue, the RPIC immediately backed the drone away from the tower, which cleared the error, and then proceeded with the mission. This was the only (and very brief) technical issue of the day, which presumably occurred when a radio equipment user transmitted just as the drone was close to the tower.

#### *Airport Ramp and Traffic Activity*

Normal airport operations continued throughout the morning, which included multiple cargo and business jet flights and a nearly constant flow of training flights. During the sUAS sorties, airport ramp activity east of the hangar and near the flight school hangar included airplanes entering the ramp for parking and passengers exiting and entering the buildings. To avoid overflight of vehicles and persons, the RPIC performed occasional brief stand-downs by hovering to a safe area or landing until the activity cleared.

During one sortie that launched from the southwest corner of the hangar toward a planned grid to cover the retention pond abeam the approach end of runway 5L, a pilot of a single-engine Cessna executed a practice engine-out landing and turned directly toward the runway numbers, cutting the corner off the typical traffic pattern. The Cessna's tighter pattern could have brought the airplane concerningly close to the sUAS flight operations area; however, both the RPIC and VO saw the Cessna turning, communicated with each other, and the RPIC responded by maneuvering the drone away from the grid. Although the Cessna and the drone never entered hazardous proximity to each other, the traffic scenario highlighted the value of close coordination and communication between the RPIC and VO.

UAS Team members later asked ATCT personnel if they could see the drone when it was flying. The tower controller stated that they had been looking for it on each sortie, but never saw it, and noted also that no pilots reported seeing it. The Cessna pilot also stated that he did not see the drone. This information regarding the difficulty (or inability) of ATCT personnel and pilots of manned aircraft to see drones served as a good reminder to the RPIC and VO regarding the importance of maintaining required VLOS with the drone and communication with each other, ATC personnel, and, if needed, pilots of manned aircraft when operating in an active airport environment (see figure 6).



Figure 6. Image captured by the drone during the mission. (Note business jet on approach to runway 5.)

By the time that the last planned sortie was completed, the storms were moving very close to the airport. The desired areas were covered, so, after one last quality check, the team packed up and headed inside the FBO just in time to avoid the rain.

### 1.3 Equipment Used

#### 1.3.1 sUAS, Cameras, and DGPS

All equipment used for the effort was commercially available, off the shelf. The team brought two drones: the primary drone used for the mission and one to have available as a

backup. The primary aircraft was a DJI Phantom 4 Pro (see figure 7) equipped with an FC6310 camera using the Sony Exmor 1-inch (in) (2.5 centimeter [cm]) complementary metal-oxide semiconductor (CMOS) sensor, which provided still photo resolution of 20 megapixels (mp) in .jpg or .raw format. The camera was equipped with a mechanical shutter, which was ideal for use in capturing images via drone to support a photogrammetry application. (Mechanical shutters avoid introducing image errors and distortions that can result from the use of an electronic rolling shutter from a moving drone.)



Figure 7. RPIC flying a Phantom 4 Pro drone during a mission sortie.

The backup aircraft was a DJI Inspire 1 equipped with the X3/FC350 camera using the Sony Exmor 1/2.3-inch CMOS sensor, which provided a resolution of 12 mp. A Trimble Geo 7X DGPS was used to record the GCPs, which were corrected using the Continuously Operating

Reference Station (CORS), which was coincidentally located less than 0.8 km (0.5 mile) away, in front of the airport fire station.

### 1.3.2 Software and Processing

To build the 3D model, the data were processed using the Pix4D Mapper software with a laptop PC compatible with the suggested specifications from Pix4D. Creating a detailed photogrammetric 3D model of an object the size of the hangar and surrounding terrain at the required resolution required about 1,000 images.

The process of developing the 3D model through Pix4D began with importing the photographs and validating the image information. During the first step, the software looked for common keypoints throughout the photographs and marked thousands of overlapping points. Although photographs taken using the drone have geographical information embedded in the meta-data, the accuracy is limited that of an uncorrected GPS – typically, within 5 to 10 m laterally with height information that can be very inaccurate. The use of GCPs substantially increased accuracy: Past experience of the UAS Team with the Geo 7X showed that, under good conditions with nearby CORS stations, positional accuracy (relative to the Earth datum) could be as good as 4 to 10 cm (1.6 to 3.9 in). (The data sheet for the Trimble Geo 7-series units describes the unit’s accuracy and reliability and the factors that may introduce anomalies [Trimble 2016].) Thus, during the first step in the processing, NTSB UAS Team members manually fine-tuned the geographic location information by viewing the images containing the GCPs taken with the DGPS and marking the pixel representing the center of each GCP.

Following the marking of GCPs, the 3D point cloud, consisting of millions of data points, was constructed. Relative accuracy (in other words, measurements within the point cloud) was

measured to approximately 2.5 cm (1 in). (This accuracy is a function of the camera distance and focal length, amount of image overlap, and other factors.) A triangulated 3D mesh was then built from the point cloud. The mesh processing (which interpolates between points) required some iterative interaction to remove artifacts in the mesh. Typical artifacts in the mesh were evident; for example, the color and texture of the hangar roof were visually similar to the color and texture of the paved ramp areas nearby, which required some manual cleanup of the cloud to build the best 3D mesh model.

Two separate final mesh files (one of the main hangar building structure and the other of the surrounding terrain, trees, brush, vehicles, and other nearby structures) were exported as a 3D model in .obj file format and provided to the CFD wind simulation specialist at Boeing (see figure 8 [Boeing 2017, 2]).

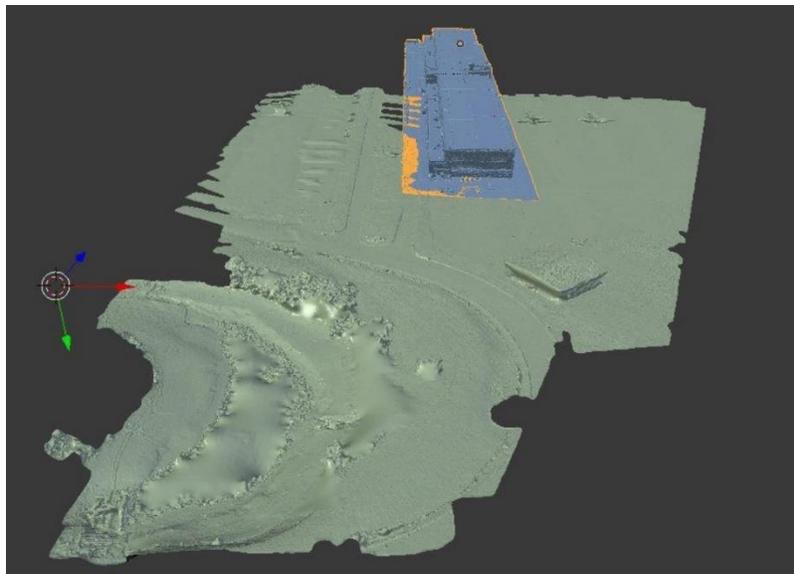


Figure 8. Three-dimensional model of hangar and surrounding terrain developed in Pix4D using imagery captured by the sUAS.

#### **1.4 Digital Preservation of Historically Significant Hangar**

Initially, the Boeing CFD specialist asked for imagery of only the southern half of the hangar. However, as the NTSB UAS Team members prepared for the mission, they learned the historical significance of the building. Known as Hangar 1, it was one of the last standing buildings of the Willow Run Bomber Plant complex that produced the Consolidated B-24 Liberator bomber during WWII, and it housed part of the Yankee Air Museum collection (Save 2018a). The Willow Run factory complex was the first plant to build bombers on an assembly line, and it was the home of the original “Rosie the Riveters,” who were part of the unprecedented expansion of women in the workforce, building part of the American “Arsenal of Democracy” (Yankee 2018b, Save 2018b).

Looking at the historic photos, it was clear to the team that the exterior of the building was essentially the same as it was in 1944 (see figure x [Norton 2016 25]). Hangar 1 was used during WWII as a maintenance depot, providing storage for completed B-24s and modified aircraft (such as radar-equipped “Pathfinders”) until ready for military deployment.



Figure 9. A 1944 photograph shows Hangar 1 on the left with a day and half of B-24 production parked on the west ramp.

According to the YIP airport master plan, Hangar 1 was scheduled to close and eventually be demolished (Willow Run 2017 5); demolition was planned for November 30, 2018 (J. Osborne, personal communication, April 3, 2018). The only historic portion of the Willow Run Bomber Plant complex planned to remain (although not in original configuration) was the adjacent portion that served as the end of the assembly line, where aircraft were fueled. (At the time of this report, that building was under renovation to house the museum [Yankee 2018b].) When the NTSB UAS Team learned that this piece of history was endangered, the initial plan to model only about half of the hangar changed: Half wasn't good enough, we decided to model the

whole thing! As a result, this historically significant building was preserved in a digital format through the imagery collected and photogrammetry output produced by the team. Further, obtaining the additional imagery to model the entire hangar did not require substantially more flight time, and the complete model was available for use in investigative analysis.

## Chapter 2

### CFD Wind Simulation

#### 2.1 Further Processing to Optimize 3D Hangar Model

The Boeing CFD specialist found that, before the 3D model mesh files provided by the NTSB UAS Team could be used effectively in OpenFoam (a widely used open-source CFD modeling software), more processing was needed (Boeing 2017, 1). The specialist combined the mesh files and used the open-source software Blender to manually make the combined mesh “watertight” with essentially no holes. The watertight combined mesh file was further processed using an OpenFoam utility to apply settings that allowed for model stability (Boeing 2017, 1). The final mesh used for the CFD model wind simulation was a blend of the combined drone mesh data inserted into a 500 by 500 m flat plane. (A flat, smooth plane was necessary along the model boundaries for model stability.) Finally, an MD-83 model was positioned in the mesh to represent the parked location of the accident airplane (see figure 10 [Boeing 2017, 2]).

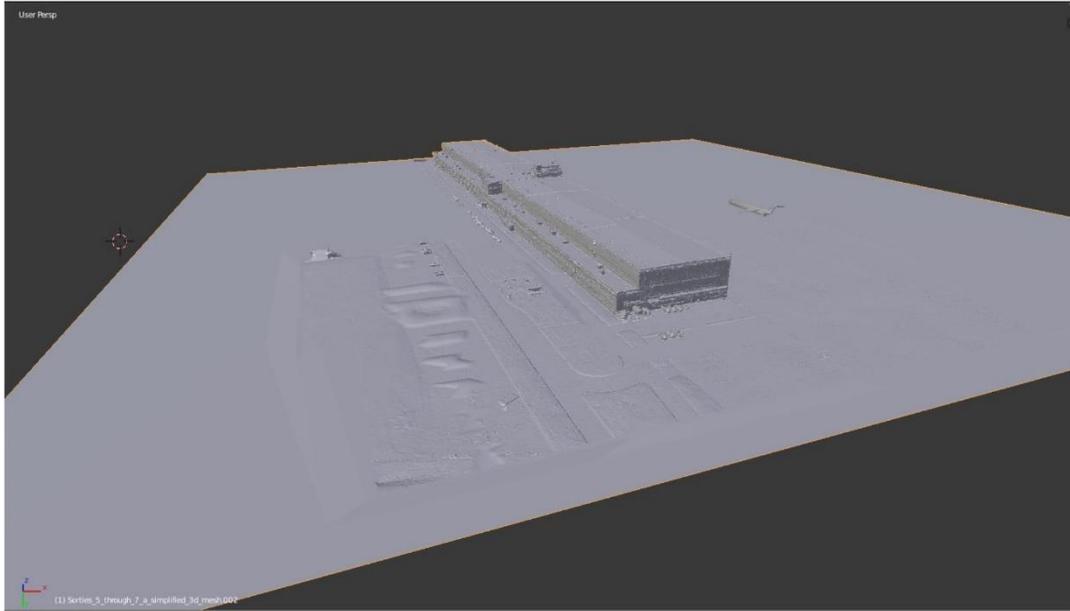


Figure 10. Final 3D mesh used for CFD model wind simulation.

## 2.2 Results of CFD Model Analysis Study

The Boeing CFD specialist used the final 3D mesh and the weather information provided by the NTSB meteorologist assigned to the investigation to perform the CFD model analysis. The weather information included variable wind magnitudes, directions, and gusts; pavement temperature; and additional meteorological data.

The wind simulation revealed that, at the accident airplane's parked location, the elevators could have been subjected to hangar-generated turbulent flow that included a small-scale 30+ m/s (58+ kts) gust moving over the airplane (Boeing 2017, 10). According to the simulation, another possibility included small-scale -15/+15 m/s (-29/+29 kts) vertical vector couplets that moved horizontally toward the airplane with the turbulent gusts and waves that were being generated downstream of the hangar (Boeing 2017, 11). Figure 11 (Boeing 2017, 10) and figure 12 (Boeing 2017, 15) provide visualizations of select wind simulation results.

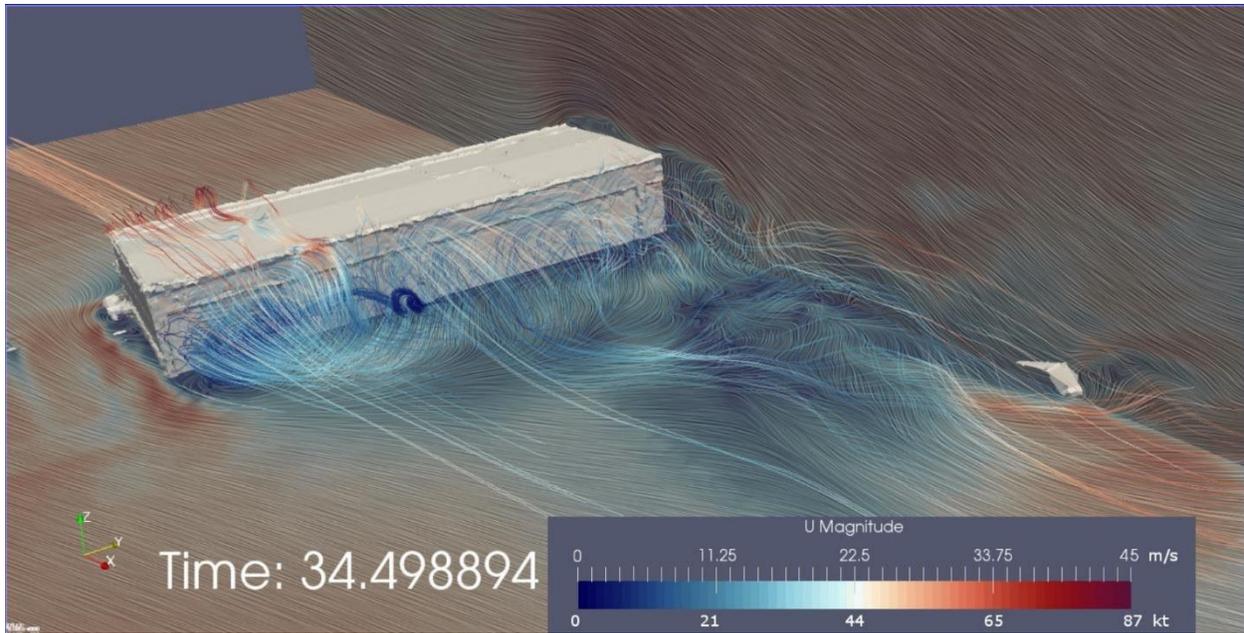


Figure 11. Three-dimensional visualization of wind simulation results for a discrete time showing turbulence generated downwind of the hangar. Note: Accident airplane’s elevators can be seen on lower right side of image.

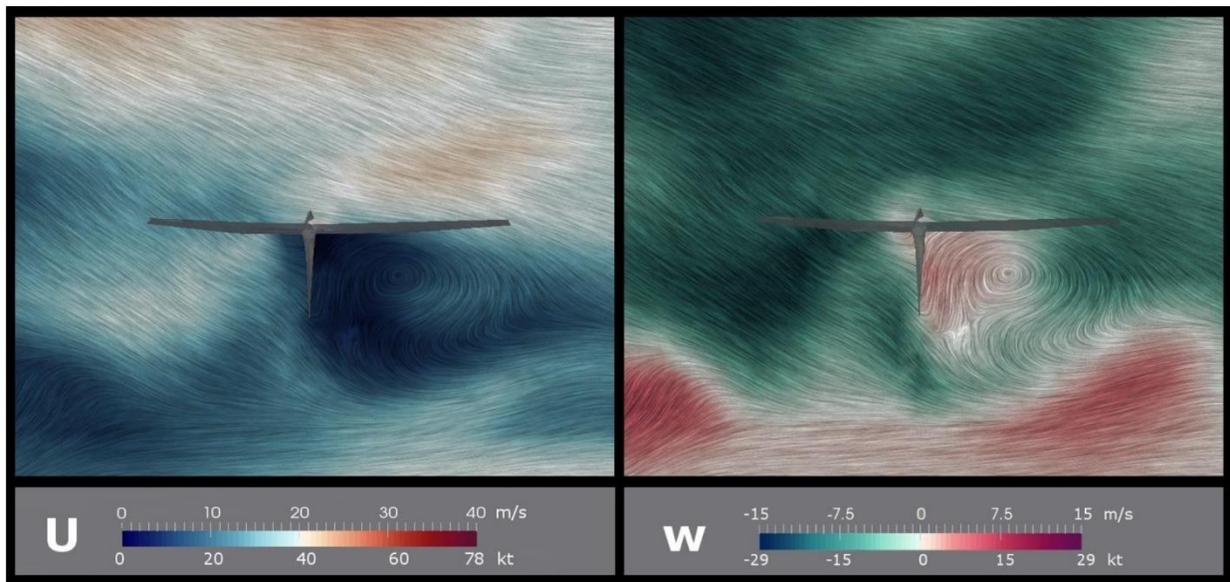


Figure 12. Vertical cross-section visualization of wind simulation results for a discrete time showing horizontal (“U”) and vertical (“w”) wind magnitudes in area of the accident airplane’s elevators.

### 2.3 Full-Scale Elevator Load Testing

As described previously, the inboard linkage components of the right elevator's geared tab were locked in an overcentered position and bent outboard, effectively jamming the right elevator and preventing airplane pitch response and rotation during takeoff. When the airplane is parked on the ground, the elevators are free to move independently within the confines of the upper and lower mechanical stops, which inhibit elevator movement in each direction. Although the elevator is designed to distribute increased loading via a torsion bar and stop arm assembly when the elevator is in contact with a stop, excessive loading can result in excessive torsion bar deflection, increasing the likelihood that the geared tab linkage could travel to an overcentered position (see figure 13).

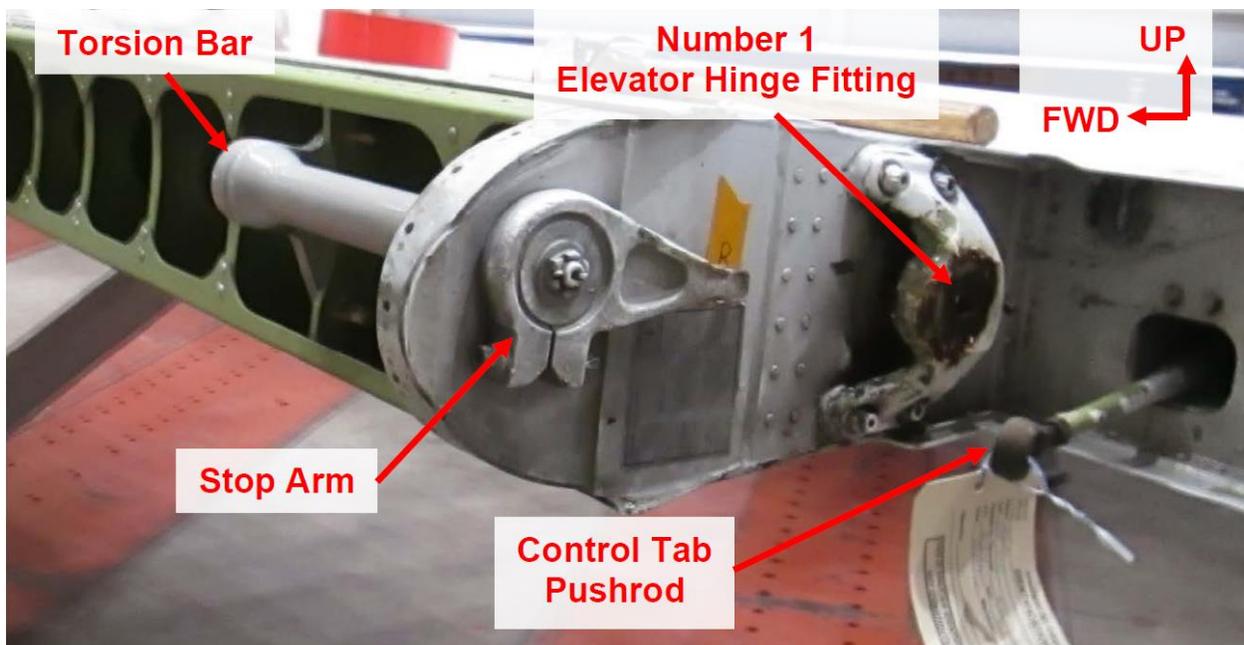


Figure 13. Elevator stop arm and torsion bar assembly.

The resulting CFD results assisted the NTSB systems investigator in designing a more representative test plan for the airplane's elevator system, more specifically the interaction with the elevator stops, which included a series of static and dynamic elevator load tests to determine

what conditions, consistent with the CFD results and the known circumstances of the accident, could enable the geared tab linkage to move to an overcentered position and jam the elevator.

In preparing the test plan, investigators used the hinge moment formula specified in 14 *CFR* 25.415 to calculate the hinge moments needed to simulate static elevator loads from ground gusts of 25, 55, 60, 65, 70, and 75 kts (the maximum recorded wind gust at YIP was 55 kts) (5). The CFD model results indicated the potential for turbulent gust flow around the airplane's elevator to induce both lifting and downward loads. Thus, for each dynamic test, the load was applied to the elevator, then the elevator was raised to either a neutral or full-trailing edge up (TEU) position (using a forklift and lifting straps) before it was released (using a quick-release mechanism). Releasing the lifted elevator from either the neutral or full-TEU position allowed it to travel downward and dynamically contact the trailing edge down (TED) stop.

None of the static test cases resulted in an overcentered condition of the geared tab linkage. Dynamic tests for simulated gust loads of 25 and 55 kts with the elevator starting in either a neutral or full-TEU position did not result in the geared tab linkage becoming overcentered. For the 60-kt simulated gust load, the linkage became overcentered for only the full-TEU initial elevator position test. For the 65-, 70-, and 75-kt simulated gust loads, the linkage became overcentered for the neutral initial elevator position tests. Based on the neutral initial position test results, tests of the full-TEU initial position were not performed.

## Chapter 3

### Conclusions: Value of sUAS to Investigation

#### 3.1 Increased Efficiency in Creating a More Accurate 3D Model

Use of the sUAS to acquire the imagery of the hangar area greatly reduced the time and labor costs required to create a 3D model of the complex building and terrain environment, which would otherwise require using blueprints, photographs, terrain data (from GoogleEarth, U.S. Geological Survey, and/or other sources), and CAD software to manually create the model. For example, it would be difficult to manually create the basic hangar structure alone, but to then add on all of the intricate accessories (duct work, chimneys, ladders, detailed architecture, bushes, trees, terrain near the river, et cetera) could take weeks of labor. Further, such a monumental effort still may not provide the level of accuracy needed.

During the process, the NTSB UAS Team learned that some additional manual processing of the 3D model created by the NTSB UAS Team was required to prepare the mesh data for effective use by the CFD software (such as sealing holes to create a “watertight” mesh, which is crucial for model stability). This understanding of the steps involved, gained through trial and error, will enable more efficient preparation and processing of future models.

For effective use in the CFD simulation, which has 0.5 m (1.6 ft) resolution, the input model must have at least that level of accuracy to model small-scale turbulent wind patterns caused by the obstructions. The Boeing CFD specialist believed that, once the processes for preparing a “watertight” mesh were understood, using them to refine drone-captured imagery was a superior method compared to other, more crude methods. The Boeing CFD specialist also

believed that drone data mesh products enabled the creation of a realistic, high-resolution model that would be difficult, if not impossible, to create manually with acceptable accuracy.

### **3.2. Value of CFD Results in Developing Elevator System Testing**

The results of the CFD, including the detailed model of the hangar, greatly increased the confidence in the wind simulation's ability to resolve the micro-climate environment sufficiently to draw conclusions about the wind's effect on the airplane's elevator. The visualization of the wind patterns in the vicinity of the tail aided in the development of the test cases, specifically the dynamic test cases. The results from the dynamic test cases helped the investigation understand the interactions of the elevator stop system during an impact-loading condition. Without the CFD study information, questions could have remained regarding whether or not the flow conditions simulated during the full-scale elevator testing were even possible given the known conditions on the day of the accident.

## Chapter 4

### Future of sUAS Use in Investigations

This cooperative and detailed investigation underscored how investigators can and should explore the confluence of modern technologies in furthering their investigations. The sUAS-based imagery, subsequently processed by current generation photogrammetry tools, provided investigators the ability to examine the environment of an accident scene to great depths. Applications (such as this example) that allow for a detailed micro-climate survey (whether affected by man-made object, as here, or natural terrain) are only the beginning. A rich 3D presentation of the accident area, with high geographical accuracy, allows for further examination such as geographic information system (GIS) analysis of airport environments, visibility evaluations, and terrain mapping and modeling. The wind study enabled by this exercise is but one of a multitude of ways to think about all the dimensions of an accident scenario and visualize everything from the overall scene and environment, down to very specific details of items.

Other applications conducted by the NTSB UAS Team include viewpoint reconstructions for both aircraft and surface vehicles, analysis of terrain at both large and small scales, and the development of accident site models that enable investigators the ability to continue to take accurate accident site measurements long after the wreckage has been cleared. The future of accident investigation will certainly take increasing advantage of this revolution in technology; with miniaturized, high-resolution cameras and precise positioning and flight plans that provide data for use in affordable, user-friendly processing programs allow investigators to link different facets of their work in new ways. The photogrammetry products developed from these efforts

provide investigators with the tools to immerse themselves in the accident evidence better than ever before. The sUAS represents far more than just a means of taking a nice aerial photograph; it is the gateway to deep analysis of the accident environment (see figure 14).



Figure 14. Two of your authors (and fellow investigators) share their sentiments on the benefits of sUAS to assist investigators now and into the future.

## Notes

1. This paper's author Michael Bauer is the NTSB Systems Group Chair assigned to the investigation.

2. This paper's author Michael Richards is the NTSB Senior Meteorologist assigned to the investigation.

3. This paper's author Matthew Grzych is the Boeing investigative party member who performed the CFD simulation.

4. This paper's author William English is the NTSB UAS Team Program Lead; author Michael Bauer is also an NTSB UAS Team member.

5. The airworthiness standards of 14 *CFR* 25.415 specify that flight control systems and surfaces must be designed for the limit loads generated when the airplane is subjected to a 65-kt horizontal ground gust from any direction while parked and taxiing. The regulation allows for the assumption of static loads and provides the formula from which the hinge moments must be computed.

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\*This document is available in the NTSB’s public docket for accident DCA17FA076, accessible from the NTSB’s Accident Dockets web page by searching the accident number.