Use of Unmanned Aircraft Systems for Land Surveys and Infrastructure Inspections

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Gilbert Gedeon, P.E.

CED engineering.ca CANADA
CPD FOR THE PROFESSIONAL

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.ca

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Tech Brief

USE OF UNMANNED AIRCRAFT SYSTEMS FOR EARTH MOVEMENTS

INTRODUCTION

This document provides information to support Unmanned Aircraft Systems (UAS) integration for detecting and monitoring earth movements. These systems may be used for many earth movement applications such as rockfall monitoring, landslide deformation analysis, post-earthquake ground deformations, and general emergency response. In many applications, change analyses are conducted through repeat surveys with UAS.

Without UAS, monitoring typically relies on either coarser airborne or satellite information (e.g., imagery or Interferometric Synthetic Aperture Radar) or ground-based methods such as Light Detection and Ranging (LiDAR) or robotic total stations. UAS platforms can be attractive for these applications because they provide a cost-effective, versatile, flexible, and rapid three-dimensional (3D) mapping approach. The speed and versatility of the platform is particularly important for monitoring earth movements in a dynamic environment. In some immediate response applications, ground movements do not allow sufficient time to conduct more traditional ground-based surveys and can pose safety risks. Hence, UAS technology could be suited to fill in this gap and may also be effective in longer-term monitoring programs.

FEDERAL AVIATION ADMINSTRATION REGULATIONS

UAS operators in both the public and private sectors must also adhere to statutory and regulatory requirements. Public aircraft operations (including UAS operations) are governed under the statutory requirements for public aircraft established in 49 USC § 40102 and § 40125. Additionally, both public and civil UAS operators may operate under the regulations promulgated by the Federal Aviation Administration (FAA). The provisions of 14 CFR part 107 apply to most operations of UAS weighing less than 55 lbs. Operators of UAS weighing greater than 55 lbs may request exemptions to the airworthiness requirements of 14 CFR part 91 pursuant to 49 USC §44807. UAS operators should also be aware of the requirements of the airspace in which they wish to fly as well as the requirements for the remote identification of unmanned aircraft. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/

BENEFITS AND CHALLENGES

UAS technology may offer multiple benefits when monitoring earth movements compared with other alternatives, including:

- **Safety**
    - Earth movements tend to occur in steep, mountainous or hilly regions where space for conventional ground-based surveys is limited. These movements also disrupt survey control.

  - Terrain susceptible to earth movements is often rugged and difficult to walk on because of frequent movement, which makes it challenging for crews with bulky survey equipment to acquire conventional measurements. With UAS, data may be collected across the landslide with relative ease as crews may avoid traversing the terrain in many cases. Note that some access may still be needed to set ground control points (GCPs), but these can often be placed strategically in more accessible locales.
  - Crews could be located in a safe location farther away from the slope, away from falling rocks, deep tension cracks, and other hazards.
  - Crews would be able to operate away from the roadway, which is particularly important given that landslides could result in access limitations on roadways including rough roads, cracking, rutting, and other pavement distresses.
- **Versatility**
  - UAS could be an effective tool to analyze a wide range of sites ranging from small slope failures to slopes along corridors several miles long.
  - UAS platforms can support several sensors, including red, green, and blue (RGB) cameras, LiDAR, and hyperspectral images that may be helpful for characterizing the morphology and geology of a site.
- **Productivity**
  - UAS platforms may efficiently cover a large site compared with ground-based solutions.
  - UAS platforms could allow the terrain to be viewed efficiently from multiple vantage points, enabling effective coverage across the site. While Structure from Motion (SfM)/Multi-view Stereo (MVS) photogrammetric techniques cannot see through dense vegetation to acquire terrain, some effects of vegetation blockage can be mitigated by flying the UAS to acquire data behind a tree or bush to help in areas of light to moderate vegetation that are often blocked from road-based, ground LiDAR surveys of steep slopes.
  - The ability to meticulously plan the flight path (e.g., height, speed, overlap) could result in more uniform data across the site compared with ground-based LiDAR, which is helpful for generating accurate Digital Terrain Models (DTM)s and performing analyses.
- **Flexibility**
  - The lightweight nature of UAS may enable them to be easily deployed in an emergency situation or in response to a hazardous event.
- **Reliability**
  - Setting conventional GCPs that are stable for reference marks can be challenging. UAS could use real-time kinematic/post-processing kinematic (RTK/PPK) global navigation satellite system (GNSS) solutions for direct georeferencing which would minimize the need for GCPs.

Challenges and considerations when operating UAS in these environments include:

- Operating UAS in steep terrain can be challenging. Some of these issues may be mitigated with terrain-following piloting software; however, extra care should be taken on steep terrain with tall vegetation, particularly in narrow canyons.
- RTK/PPK positioning capabilities may be needed when monitoring earth movements because access to place GCPs at these sites is often limited. Additionally, given the unstable nature of the terrain, it can be difficult to set reliable, long-term reference points for GCPs.
- UAS usage close to the highway may cause driving distractions (Barlow et al. 2019), which could be especially hazardous when operating on steep, mountainous roads.
- Conflicts can arise with manned aircraft operations for emergency response efforts that may not allow the use of UAS in the area of interest.

- In many cases, landslide/rockfall sites are remote, and cell/data connections may not be available for uploading UAS data or transmitting other information from the field.
- Given the rugged, windy, steep terrain, it could be difficult to maintain line of sight with the UAS; multiple operation locations may be needed. In addition, finding suitable take-off/landing locations can be challenging given the ruggedness of the terrain and vegetation.
- Wildlife (particularly birds) may feel threatened by the aircraft and react in a way that poses additional challenges.
- Weather hazards (snow, rain, and strong winds) common to mountainous terrain could substantially limit windows of operation.
- Maintaining the stability necessary for high-quality images without blurring can be difficult with adverse conditions common in canyons (e.g., winds, rain, snow).

PROCEDURES

This section summarizes common data collection and processing procedures and protocols found in use at State DOTs (Federal Highway Administration, 2018).

DATA COLLECTION OPERATIONS

When monitoring earth movements over time or responding to them, the following should be considered:

- Identify locations of stable ground control
- Determine the frequency of surveys of the earth movement area of interest
- Determine the number and distribution of GCPs.

The data collection plan can then be designed to ensure project specifications are satisfied. Data collection mission parameters such as acquisition height, image overlap settings, camera angles for data collection, and flight line patterns may be determined using mapping planning software which could significantly influence the resulting project accuracy.

Other factors to be considered when planning the survey may include (1) take-off/landing point and flying height, (2) the overlap between flight lines (higher in vegetated areas), (3) the speed of acquisition (which affects resolution), (4) sensor characteristics, (5) inaccessible areas, and (6) topography, which is often complex and variable in the case of a landslide which by nature disrupts terrain. Maintaining a constant flight height may be difficult and ultimately could affect the ground resolution as the topography changes. Depending on the changes in topography, in some cases it may be advantageous to fly parallel to the slope and work upward, while in others it may be better to fly perpendicular. It may be helpful to consider having some flightlines intersect at 90-degree angles to validate the calibration of the Inertial Navigation System. Figure 1 provides an example of a data mission layout plan.

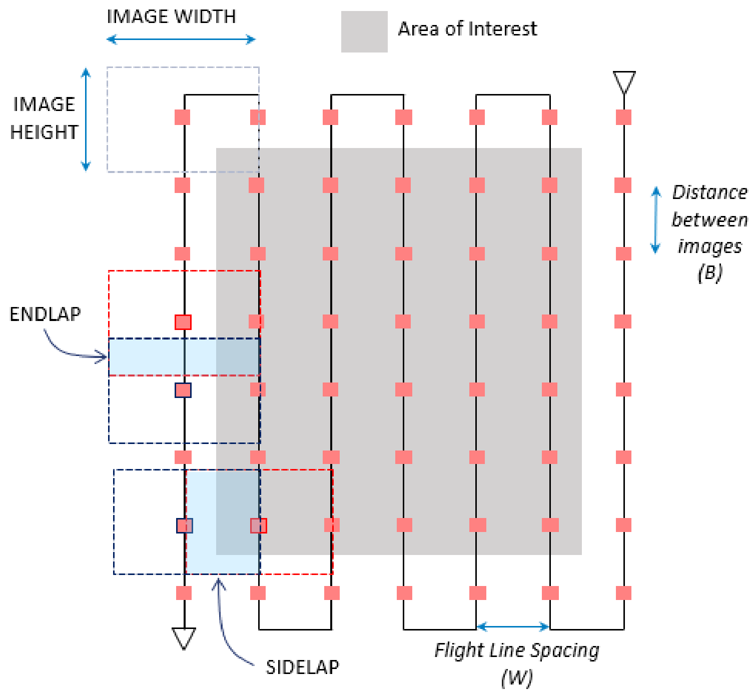


Figure 1. Example data mission layout (Source: FHWA)

Once the general flight path is established, a more detailed analysis of expected ground-sampling distance (GSD) (GSD, pixel size or spacing between LiDAR points) can be obtained from the flight lines to optimize the flying geometry. Flight altitude is one of the most influential factors affecting the quality of the end product. Overlap settings (front and side overlap) and the orientation for best data capture should be determined. A DTM is necessary to obtain a more accurate estimate. GSD is a function of the flying height, flightline configuration, sensor characteristics, and speed. In addition, when estimating the point density from LiDAR scans, it may be helpful to consider that the GSD is not representative of actual ground points because the analysis does not account for vegetation.

When designing the flight lines, it may be helpful to capture a larger area than needed to provide some data in "stable" locations next to a landslide so that change detection results can be validated and biases between surveys can be determined. In addition to be distributed throughout the area, GCPs should be placed to bound the survey area. However, GCPs placed at the edges of the surveyed area may not be well-captured.

EARTH MOVEMENT ANALYSES USE CASES

ROCKFALLS

UAS technology may be beneficial in analyzing rockfall activity and stability of rock slopes. Applications could include:

- Obtaining the big picture and localized detail of geomorphic processes (e.g., fracturing, weathering).
- Computing the rockfall activity index (RAI) (Dunham et al. 2017) to characterize the slope morphology and identify areas with highest risk.
- Performing change detection and monitoring of the rock slope.
- Computing volumes of rockfalls, identifying clusters, and creating magnitude frequency relationships to quantity and compare risk between rock slope segments.

Use of UAS technology for remote surveying of rock slopes may have advantages over conventional methods. First, UAS can have safety benefits over inspectors gathering information while climbing slopes to investigate issues. Next, the detailed point clouds and image analysis from UAS could provide quantitative, systematic data compared with conventional rockfall hazard rating systems, where results may vary from inspector to inspector. Lastly, the flexibility of the viewpoint of the UAS may improve cliff views compared with terrestrial or mobile laser scanning, especially on benches, on the upper sections of slope that result in data gaps.

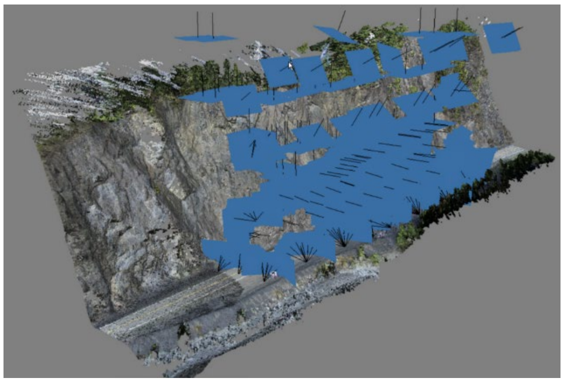


Figure 2. Figure of a SfM/MVS-derived point cloud of a rock slope on the Glenn Highway in Alaska. Camera location, orientations, and focal planes for each image are shown. Image Source: O'Banion et al., 2018

O'Banion et al. (2018) performed a detailed comparison of UAS-SfM/MVS data to terrestrial LiDAR for several rock slope sites along the Glenn Highway in Alaska (Figure 2). In this study, the UAS was flown in manual mode to capture images from multiple vantage points. Note the unstructured nature of the photograph acquisition due to the lack of flight planning software to support auto image acquisition for vertical features at the time of survey. In comparison to the terrestrial LiDAR data, the following observations were made:

- Sharp edges from rock discontinuities were rounded and smoothed compared with LiDAR data.
- UAS SfM outperformed LiDAR for seeing beneath and behind sparse vegetation.
- In dense ground cover/vegetation, LiDAR outperformed drone SfM (active vs. passive light source).
- Many artifacts were observed in boundaries of SfM model.
- Survey control targets were placed across the scene; however, they could only be placed at the bottom of the cliff due to accessibility constraints and safety reasons. This resulted in error propagation and drifting of some models toward the top of the cliff.
- The errors in SfM depended on the distance, quality of texture for key point matching, lighting conditions, and quality of GCPs.

In research for the Pacific Northwest Transportation Consortium (PacTrans) and the Oregon Department of Transportation (ODOT), Olsen et al. investigated the suitability of UAS technology for change detection of rock slopes (Olsen et al. 2021). Figure 3 shows some example data products from this investigation, including a clustering analysis to identify individual rockfall features between two epochs of data completed in a processing software (Olsen et al. 2021). The volume of each rockfall cluster can be computed, and a magnitude frequency curve can be generated such as those shown in the right plot. Magnitude frequency curves relate the hazard between sites and show the distribution of how often small rockfall events vs. large rockfall events happen at a site as well as the overall amount of rockfall happening at the site (i.e., as the curves move upward, they show increased activity at the site). These magnitude frequency curves follow a power law relationship.

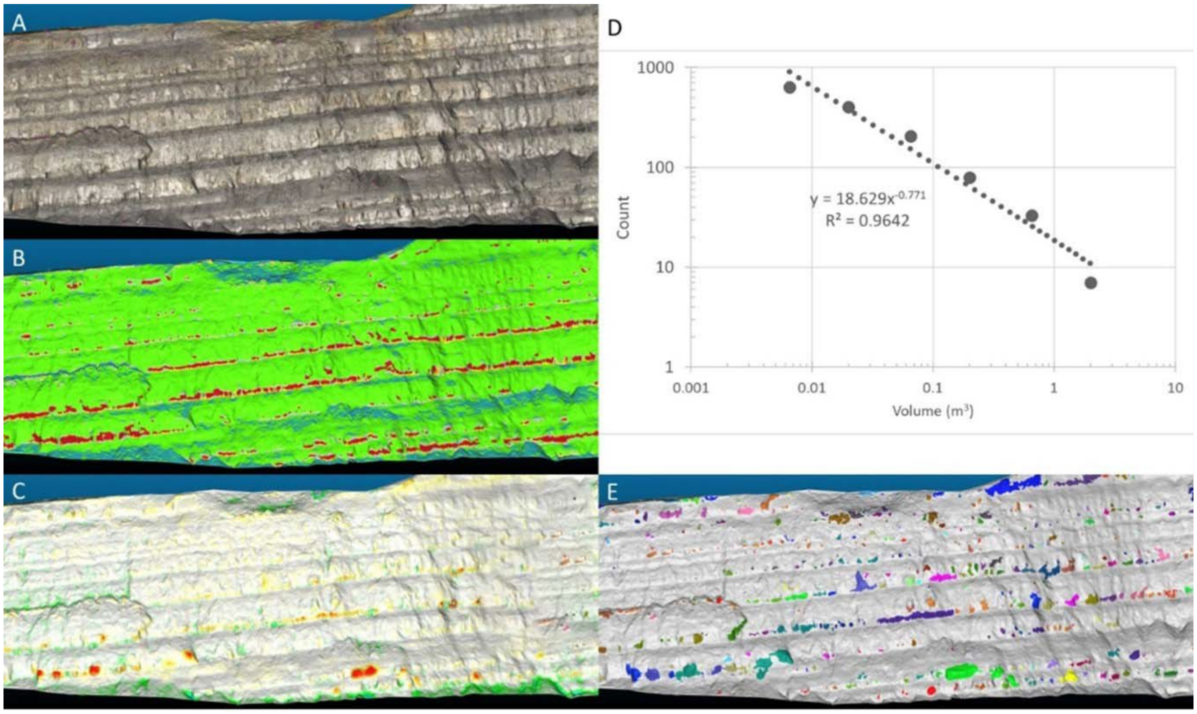


Figure 3. Example UAS-SfM/MVS geomorphological analysis for a rock slope in Eddyville, Oregon. (A) RGB photographic information texture mapped to a digital terrain model. (B) RAI morphological analysis showing areas of overhang, talus and intact rock. (C) Change detection analysis results. (D) Magnitude frequency relationship showing the distribution of rockfalls based on volume. (E) Individual rockfall cluster analysis for developing the magnitude frequency distributions. Image Source: Oregon State University

TAKEAWAYS

Oregon State University (OSU) and the Oregon DOT learned the following from using UAS technology for rock slope assessment:

- Many flight planning software packages may not be reliable for vertical, complex topography such as rock slopes. For these situations the UAS can be operated in manual mode. (Some software does allow for developing flight plans for towers – cylindrical or rectangular objects.)
- Generally, targets for SfM reconstruction can only be safely placed at the base of the cliff, which can lead to error propagation of the surface reconstruction with SfM/MVS algorithms toward the top of the slope.
- Acquisition of ground photos can complement the UAS photographs (e.g., higher resolution camera, better captured targets) and significantly improve results. In particular, the ground-based photographs can often capture the base and top of the rock outcrop within the same photograph, limiting drift issues discussed in the previous bullet.
- With adequate survey control and careful processing, SfM/MVS can approach the accuracy of terrestrial LiDAR for rock slope assessments.
- SfM/MVS can provide higher resolution results compared with terrestrial LiDAR and provide a more uniform point distribution on the surface. The platform flexibility also reduces data gaps by allowing data to be captured from multiple perspectives and vantage points.

LANDSLIDES

UAS technology may support a variety of applications for landslide assessment, including identifying landslide features (e.g., scarp, debris, extents/boundaries, tension cracks, damaged structures); change analysis between epochs; and tracking movements across an active flow slide.

Babbel et al. (2019) explored the use of UAS LiDAR to investigate the Spangler Landslide in Molalla, Oregon. The change analysis (Figure 4) of the UAS LiDAR DEM (Digital Elevation Model) was performed with respect to an airborne laser scanning (ALS) data set collected in 2009 by the Oregon LiDAR Consortium and yielded several important observations regarding the landslide. First, a graben is apparent from the change detection results (represented as a red section [subsidence] traversing the road). A graben is a block that subsides at the head of a landslide, wedged between the landslide body and headscarp. Thus, the vertical settlement is notable at the head of the landslide. The road appears as accretion (blue) as a result of repaving and reconstruction at the onset of slope failure. Second, throughout the landslide body, a region of accretion (i.e., heave/advance) is observed, represented in blue. The observed accretion from change detection occurs as the generally translational movements of the landslide body, resulting in an apparent increase in the elevation of the downslope embankment. Third, most of the displacement is occurring at the northwest portion of the slide, likely due to increased groundwater levels from a recently installed pond at the bench, west of the headscarp. Lastly, the DEM highlights numerous similar failures within the overall landslide complex. The current failure zone is likely the next calving block from a loss of lateral support from adjacent failures to the northwest as well as a relatively high ground water table.

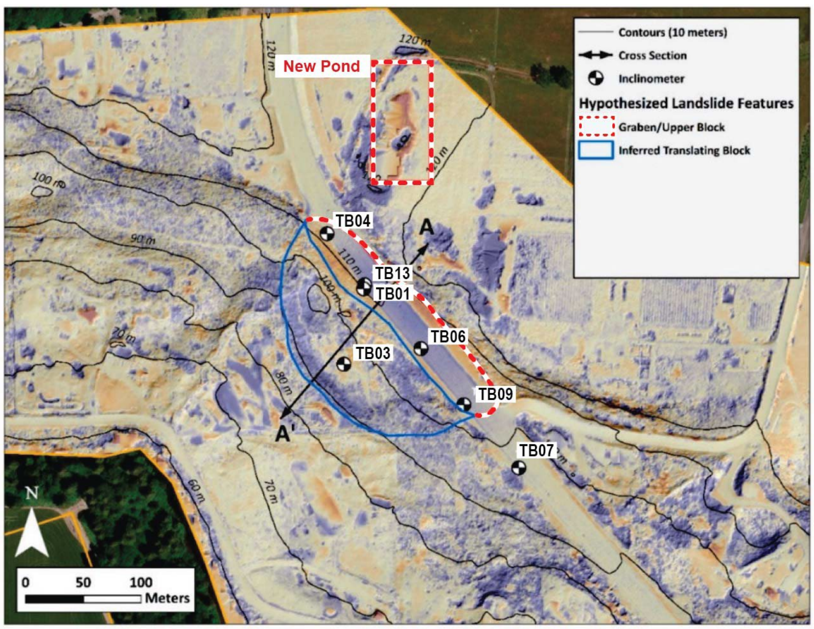


Figure 4. Change analysis of the UAS LiDAR DEM for the Spangler Landslide. Image source: Babbel et al., 2019

TAKEAWAYS

Key takeaways from this example include:

- UAS LiDAR is an efficient and cost-effective technique to map a landslide complex at high resolution and with good accuracy.
- Observations correlated well with findings from inclinometers.
- In topographic scenes with minimal planar objects, software calibrations for determining the lever arm offsets and strip adjustments can be erratic if the software was designed to detect structures and planar objects.

- Some ground filters are biased to the lowest points on a surface rather than smoothing between the low points. This can introduce a slight bias (about 5 centimeters) even on hard surfaces given the noise levels of the system.

COASTAL EROSION AND LANDSLIDING

This section explores the Hooskanaden landslide on the Oregon Coast. Researchers from OSU are monitoring this site to evaluate long-term climate impacts on coastal erosion and landslide activity. UAS can be an important tool in coastal erosion and landslide evaluation surveys to quantify erosional patterns, quantify and show distribution of landslide movements, relate erosional patterns with landslide movement, and characterize the landslide and determine its extents.

HOOSKANADEN

The Hooskanaden slide is in Oregon along the coast near the California border. The main slide is nearly half of a mile long and over 1,800 feet wide and frequently results in damage to Highway 101. Large movements require frequent maintenance and repaving of this section several times a year.

The steep terrain, vegetation, and windy conditions present challenges for the UAS data acquisition. However, ALS surveys are too infrequent to capture movements, and TLS surveys are difficult to safely complete because of the terrain.

Despite these challenges, several UAS surveys have been completed at this site to date. Flights were planned with flightlines oriented north-south to follow the contours of the landslide. Terrain follower software was also implemented to improve the safety of the field operation and quality of the results given the variability of elevation across the slide and the ruggedness of the terrain. For terrain follower, the user inputs a DEM so that the UAS can use that information and follow at a constant height above that DEM.

Another challenge of using UAS is when the slide is actively moving during the survey. GCPs can not be used as the main georeferencing framework option given that the terrain is shifting. For this application, RTK GNSS UAS is critical to minimize the survey time required. After a major failure in February 2019, several UAS flights were conducted (approximately 20 minutes each) to capture detailed orthophotographs as the slide was actively moving (approximately 1-2 feet per hour) for several days after the main rupture. To aid with the georeferencing, five GCPs were placed outside the active area of movement and surveyed before and after each flight.

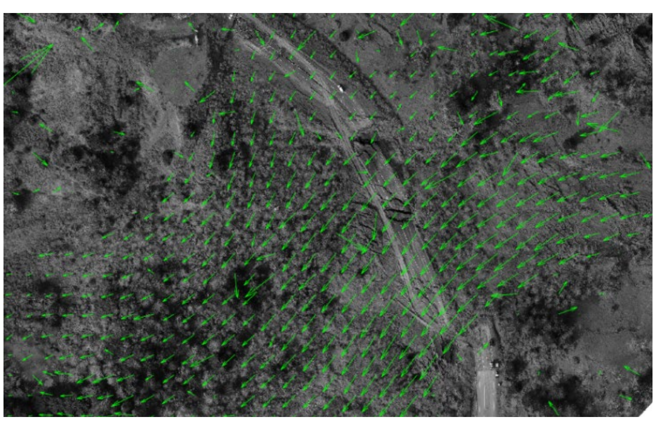


Figure 5. Digital Image Correlation Analysis conducted on the Hooskanaden slide from two flights approximately 18 hours apart while the slide underwent active movement (~1-2 ft per hour). Image Source: OSU

Digital image correlation analyses were conducted on the orthophotos obtained from the RTK GNSS UAS flights (Figure 5). These analyses were helpful to show the patterns of movement across the slide. For example, the pattern of movement rotated for the northern section compared with the southern section that tended to continue to flow southwest. To the west (left) in Figure 6, a zone of compression occurs as the vectors get shorter at the toe of the slide. But while several epochs of data were acquired, some data were lost due to technical glitches in the UAS where images were not stored on the memory card.

The orthoimage was important to detect and identify features across the landslide. Figure 6 (left) shows the damaged road section and status of the temporary access road built to quickly reopen the highway. Figure 6 (right) shows an example of tension cracks that are present across large areas of the slide.

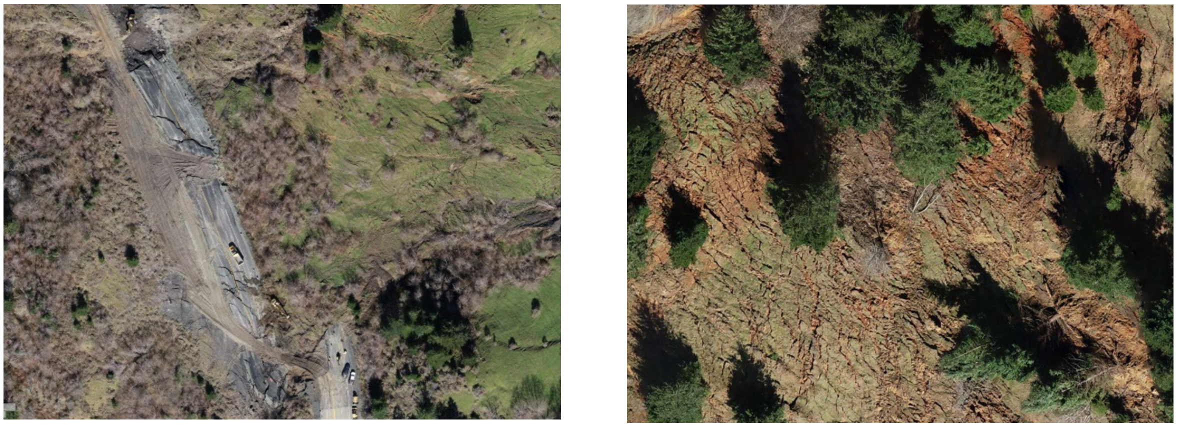
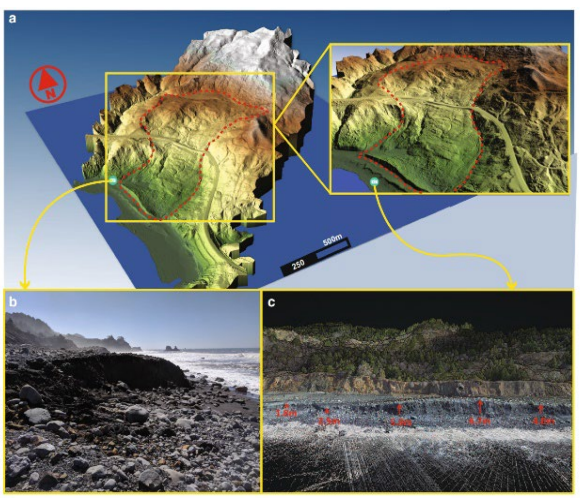


Figure 6. Example orthophotos obtained at the slide showing the damaged roadway (left) and tension cracks (right). Image Source: OSU



Given the extra time required, the UAS LiDAR survey could not be completed until the slide slowed back down so that data would be consistent between flights. However, the detailed DEMs generated from the UAS LiDAR (Figure 7) provided more rigorous quantitative information on the final condition of the slide, particularly in the areas of dense vegetation where bare earth could not be accurately modeled with SfM/MVS photogrammetry.

Figure 7.5 A. 3D view of the UAS data obtained March 15, 2019. Image source: Babbel, 2019. B. Photograph showing uplifted beach cobbles and boulders forming a secondary bluff. Image source: OSU. C. Vertical displacements extracted from the UAS. Image source: Alberti et al., 2020

CONCLUSIONS

UAS may improve safety, efficiency, and data resolution for earth movement applications while still meeting accuracy requirements in most situations. Specific highlights include:

- Both UAS LiDAR and photogrammetric methods can be powerful techniques for landslide and rockfall characterization and assessment.
- UAS technology can provide more viewpoint flexibility than other remote-sensing techniques.
- Ground control can be difficult to set on harsh landslide terrain, especially on rock slopes or if the landslide is actively moving. Using an RTK GNSS drone system with minimal GCPs can be effective in these situations where speed is important.
- Typical photogrammetric GCPs are not reliably captured in UAS LiDAR, which tends to rely on the direct georeferencing solution that is generally more rigorous than SfM/MVS operations.

REFERENCES

Alberti, S., A. Senogles, K.E.P. Kingen, A.M. Booth, P. Castro, J. DeKoekkoek, K. Glover-Cutter, C. Mohney, M.J. Olsen, and B. Leshchinsky. 2020. The Hooskanaden Landslide: historic and recent surge behavior of an active earthflow on the Oregon Coast. Landslides. https://doi.org/10.1007/s10346-020-01466-8

Babbel, B.J., M.J. Olsen, E. Che, B.A. Leshchinsky, C. Simpson, and J. Dafni. 2019. Evaluation of Uncrewed Aircraft Systems' LiDAR Data Quality. ISPRS International Journal of Geo-Information, 8(12): 532. https://doi.org/10.3390/ijgi8120532

Barlow, Z., H. Jashami, A. Sova, D. Hurwitz, and M. Olsen. 2019 "Driver Distraction Due to Drones." Transportation Research Part C: Emerging Technologies, 108: 207–222.

Carrivick, J., M. Smith, and M. Quincey. 2016. Structure from Motion in the Geosciences, ISBN: 978-1-118-89584-9.

Dunham, L., J. Wartman, M.J. Olsen, M.S. O'Banion, and K. Cunningham. 2017. "Rockfall Activity Index (RAI): A Lidar-derived, morphology-based hazard assessment system." Engineering Geology, 221: 184–192. https://doi.org/10.1016/j.enggeo.2017.03.009

Eltner, A., A. Kaiser, C. Castillo, G. Rock, F. Neugirg, and A. Abellán. 2016. "Image-based surface reconstruction in geomorphometry – merits, limits and developments." Earth Surf. Dynam., 4, 359–389. https://doi.org/10.5194/esurf-4-359-2016

Federal Highway Administration. (2018, February). Use of Unmanned Aerial Systems (UAS) by State DOTs. https://www.fhwa.dot.gov/uas/peer/2018peer.pdf

Hartzell, P., C. Glennie, and S. Khan. 2017. "Terrestrial Hyperspectral Image Shadow Restoration through Lidar Fusion." Remote Sens. 9: 421. https://doi.org/10.3390/rs9050421

Jiang, S., Jiang, C., & Jiang, W. (2020). Efficient structure from motion for large-scale UAV images: A review and a comparison of SfM tools. ISPRS Journal of Photogrammetry and Remote Sensing, 167, 230–251. https://doi.org/10.1016/j.isprsjprs.2020.04.016

O'Banion, M.S., M.J. Olsen, C. Rault, J. Wartman, and K. Cunningham. 2018. "Suitability of structure from motion for rock-slope assessment." The Photogrammetric Record 33 (162): 217–242. https://doi.org/10.1111/phor.12241

Olsen, M.J., J. Wartman, M. McAlister, H. Mahmoudabadi, M.S. O'Banion, L. Dunham, and K. Cunningham. 2015. "To Fill or Not to Fill: Sensitivity Analysis of the Influence of Resolution and Hole Filling on Point Cloud Surface Modeling and Individual Rockfall Event Detection" Remote Sens. 7(9): 12103–12134. https://doi.org/10.3390/rs70912103

Olsen, M.J., C. Massey, A. Senogles, B.A. Leshchinsky, and J. Wartman. 2021. Predicting seismically induced rockfall hazard for targeted site mitigation, ODOT SPR809 Final Report.

ONLINE RESOURCES

Federal Aviation Administration (FAA) Unmanned Aircraft Systems (UAS). https://www.faa.gov/uas/

Federal Highway Administration (FHWA) Unmanned Aerial Systems (UAS). https://www.fhwa.dot.gov/uas/

FHWA Center for Accelerating Innovation Every-Day Counts-5 (EDC-5): Unmanned Aerial Systems (UAS). https://www.fhwa.dot.gov/innovation/ everydaycounts/edc_5/uas.cfm

Tech Brief

USE OF SMALL UNMANNED AIRCRAFT SYSTEMS FOR ROADSIDE ASSET MANAGEMENT

Introduction

Small Unmanned Aircraft Systems (UAS) may assist State Departments of Transportation (State DOTs) with the management of transportation assets. The United States contains almost 4 billion miles of roadway and 600,000 bridges that serve as essential infrastructure within the national transportation and economic systems (FHWA, 2017). In turn, those assets include other types of supporting structures or assets such as High Mast Light Poles (HMLP), overhead signs, culverts and pipes, and pedestrian access ramps. UAS can assist State DOTs with the management of these assets.

Key Takeaways

- UAS may be helpful throughout the entire lifecycle of transportation asset management.
- UAS can increase safety when inspecting transportation infrastructure and supporting assets.
- State DOTs are reporting increased safety, efficiency, and cost savings by using UAS as a supplemental tool.

State DOTs are required to update every four years, its Transportation Asset Management Plan that outlines their assets and the management, forecasting, funding strategies, planning, and overall lifecycles of said assets (23 U.S.C. 119(e)(6)(B); FHWA, 2018a, p.2). Asset management is defined as "a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based on quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life cycle of the assets at minimum practicable cost" (23 U.S.C.101(a)(2)).

UAS are a supplemental tool that nearly all State DOTs have adopted for transportation asset management (AASHTO, 2019).

Use Cases

This document provides established use cases regarding the integration of UAS by State DOTs in roadside asset management.

High Mast Lighting Poles

Figure 1. UAS Inspecting HMLP. Source: NJDOT

The New Jersey DOT (NJDOT) uses UAS to assist with its inspection of 250 HMLP. NJDOT noted that traditional inspections of HMLP using binoculars result in a lack of data collection and limitations to the angles necessary for a thorough inspection (Stewart et al., 2018). Secondary inspections are often needed for a closer look that are done with bucket trucks. The use of these bucket trucks involves lane or shoulder closures that may negatively impact the public and present risks to highway workers such as work zone intrusions, equipment operator injuries, and car crashes.

While the lighting structure is still in, the UAS can be used to perform a steady, full 360-degree rotation inspection of the outer area, underneath area and the top of the lighting structure.

Inspection crews can also use the UAS to provide key aerial perspectives while the lighting structure is lowered down using the pulley system. The aerial perspective is especially helpful in identifying when the lighting structure coming down unevenly (Puppala & Congress, 2019). UAS can be used to further investigate these types of concerns and collect information that can then be used to determine if repairs are needed.

Figure 2. UAS Image of HMLP Lighting Assembly. Source: TxDOT

Figure 3. UAS Inspection of HMLP. Source: NJDOT

UAS also can be used to inspect the pole itself from the ground level to the top of the pole. With strategically planned flight paths, inspection crews can quickly inspect all sides of the pole while gathering important data on the condition of the pole itself.

State DOTs have found that using UAS for HMLP inspections has led to increased safety by reducing work zone and operator injury risks. UAS have also increased efficiency by gathering the required data with the primary inspection and have resulted in savings in labor hours and equipment (Stewart et al., 2018).

Culverts and Pipes

The Oregon DOT (ODOT) has researched the use of UAS to assist with the inspection of culverts and pipes. Imagery and videos from UAS can be used to inspect many characteristics of culverts and pipes including identification of cracking, documentation of material condition, detection of leakage, and inspection of joints and gaskets. ODOT found that UAS are an effective inspection tool for conduits and pipes that present excessive safety risk to humans or when remote vehicles can't be used, as seen in Figure 4.

Figure 4. UAS Inspection of Deteriorated Culvert. Source: ODOT

Figure 5. UAS Inspection of Large Pipe. Source: MDOT

The Maryland DOT (MDOT) has also used UAS for confined space inspection which enables the operator access to difficult locations that may be cost prohibitive if inspecting using other means (Alexander, 2021).

Many benefits are realized from using UAS for culvert inspection, aside from achieving data capture in areas difficult to access. UAS may be used in certain contaminated areas where humans would otherwise not enter. Not only time can be saved by using UAS for confined space inspection, but cost savings can be realized by the reduction in specialized equipment necessary for mobilizing humans into the proper position to carry out hands-on inspection (Alexander, 2021).

Overhead Signs

The Utah DOT (UDOT) has used UAS to help with the inspection of roadway overhead signs. UDOT has traditionally inspected overhead signs using bucket trucks that are positioned in the shoulder or in a roadway lane. This equipment requires the closure of lanes of traffic and active or passive traffic control. UDOT reports how time consuming this process of traditional inspection is, resulting in an average of two signs inspected each day. When UDOT began using UAS to inspect the overhead signs this number was increased to an average of 16 signs per day. UDOT reported a $100,000 savings on the overhead signs inspection project using UAS (Wheeler, 2022).

Figure 6. UAS Overhead Sign Inspection. Source: UDOT

Pedestrian Access Ramps

UDOT has also used UAS and remote sensors to analyze pedestrian access ramps. UAS, equipped with high-resolution sensors can capture detailed aerial imagery, which can be used to create three-dimensional (3D) point clouds of pedestrian access ramps. This data provides invaluable insights into the condition, compliance with accessibility standards, and potential hazards of these ramps. Traditionally UDOT engineers use a tape measure and smart level to inspect the slope of the pedestrian ramp to determine if it is within design standards and tolerances (Farhadmanesh et al., 2022).

Figure 7. 3D Model of Pedestrian Ramp. Source: UDOT

Using UAS and remote sensors, UDOT collected data of various pedestrian ramps and created 3D models to analyze compared to traditional in-field measurement inspections. Figure 7 shows a 3D model produced using photogrammetry. It was found that using these data collection and analysis methods resulted in highly accurate slope measurements and was a viable tool that could be used to assist with these inspections (Farhadmanesh et al., 2022).

FAA Regulations

UAS operators in both the public and private sectors must also adhere to statutory and regulatory requirements. Public aircraft operations (including UAS operations) are governed under the statutory requirements for public aircraft established in 49 USC § 40102 and § 40125. Additionally, both public and civil UAS operators may operate under the regulations promulgated by the Federal Aviation Administration. The provisions of 14 CFR part 107 apply to most operations of UAS weighing less than 55 lbs. Operators of UAS weighing greater than 55 lbs may request exemptions to the airworthiness requirements of 14 CFR part 91 pursuant to 49 USC §44807. UAS operators should also be aware of the requirements of the airspace in which they wish to fly as well as the requirements for the remote identification of unmanned aircraft. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/.

Conclusion

UAS have become a widely used tool across State DOTs and many transportation asset management use cases have been established (AASHTO, 2019). The management of transportation infrastructure, encompassing an extensive network of roadways, bridges, high mast light poles, culverts, pipes, overhead signs, pedestrian ramps, and many other assets is a complex and critical task. UAS technology has emerged as a supplementary tool that enhances the efficiency, safety, and cost-effectiveness of asset management processes. By adopting UAS for inspections and data collection, State DOTs have been able to achieve an array of advantages, including improved safety, reduced operational costs, and enhanced data quality (FHWA, 2018b).

References

American Association of State Highway and Transportation Officials (AASHTO). (2019, May). AASHTO UAS/Drone Survey of All 50 State DOTs. https://uas-aam.transportation.org/aashto-research/

Alexander, J., Robey, D., Gaus, J., and Williams, G. (2021, July 1). MDOT culvert inspection. https://rosap.ntl.bts.gov/view/dot/60113

Farhadmanesh, M., C. Cross, & Rashidi, A. (2022, August 1). Image-Based 3D reconstruction of Utah roadway assets. https://rosap.ntl.bts.gov/view/dot/64749

Federal Highway Administration (FHWA). (2017, June 27). Asset Management Overview. https://www.fhwa.dot.gov/asset/if08008/amo_06.cfm

Federal Highway Administration (FHWA)a. (2018, February). Transportation Asset Management Plan Development Processes Certification and Recertification Guidance. https://www.fhwa.dot.gov/asset/guidance/certification.pdf

Federal Highway Administration (FHWA)b. (2018, February 27). Use of Unmanned Aerial Systems (UAS) by State DOTs. https://www.fhwa.dot.gov/uas/peer/2018peer.pdf

Federal Highway Administration (FHWA). (2022, March). FHWA Work Zone Facts and Statistics. https://ops.fhwa.dot.gov/wz/resources/facts_stats.htm

Metropolitan Engineering Consulting & Forensics. (2016, August). Bridgeriggers' Aspen A-75 under-bridge inspection crane overturns on Sakonnet River Bridge in Rhode Island; 2 workers saved with minor injuries. http://metroforensics.blogspot.com/2016/08/bridgeriggers-aspen-75-under-bridge.html

Puppala, A., & Congress, S. (2019, February). Implementation of Unmanned Aerial Systems Using Closerange Photogrammetry Techniques (UAS-CRP) for Quantitative (Metric) and Qualitative (Inspection) Tasks Related to Roadway Assets and Infrastructures: Final Report. https://library.ctr.utexas.edu/hostedpdfs/uta/5-6944-01-ipr1.pdf

Stewart, B., Stock, D., and Titze, C. (2018, October 1). High mast drone inspection. https://rosap.ntl.bts.gov/view/dot/62002

Wells, J. (2022). Bridge Inspections Utilizing UAS – Implementation Program [Presentation].

Wheeler, P. (2022). Overhead Sign Inspection with UAS [Presentation].

Online Resources

Federal Aviation Administration (FAA) Unmanned Aircraft Systems (UAS). https://www.faa.gov/uas/.

Federal Highway Administration (FHWA) Unmanned Aerial Systems (UAS). https://www.fhwa.dot.gov/uas/

Tech Brief

USE OF SMALL UNMANNED AIRCRAFT SYSTEMS FOR CONSTRUCTION QUANTITY ESTIMATION

INTRODUCTION

Multiple Departments of Transportation (DOTs) have reported using unmanned aircraft system (UAS) as a tool for multiple tasks over different construction phases such as pre-construction mapping and surveying, construction progress tracking, quality control, quantity estimation, traffic control inspection/monitoring, and safety inspection. Nearly all State DOTs are using small unmanned aircraft systems (small UAS) to improve safety and collect data faster and better (AASHTO 2019). The fast-growing market of UAS has stimulated the expansion of its application in various sectors of the economy (Zhou 2018). Small UAS are being used for various quantity estimation/verification tasks, including earthwork, stockpiles, and paving estimates. Construction quantity estimation is a significant cost item on infrastructure construction projects. Because earthwork and stockpiling are largely influenced by unstable construction conditions, they may have an effect on cost control during construction. Precise estimates of actual earthwork, stockpiles, and paving volumes are important to both owners and contractors.

In infrastructure construction projects, surveying as-built conditions traditionally has relied on robotic total stations and tachymetry. These technologies can be labor-intensive, expensive, and prone to human error. Technologies such as global positioning systems (GPS), terrestrial laser scanning, and air or space-borne sensors have been used as alternatives, but they have limitations regarding cost, measurement range, and accuracy. Using small UAS as a data acquisition platform and a measurement instrument is attractive for many users surveying applications in civil engineering because small UAS can offer a cost-effective and rapid three-dimensional (3D) mapping approach.

This document provides information about successful UAS integration–specifically into construction quantity estimation practices. Surveying tools are evolving and can produce 3D accuracy that is equal to or better than conventional aerial photography (Willis 2013). Changes in land surveying within the last 20 years have been significant (Reed 2015). Enhancements to the state of the art, such as GPS, Light Detection and Ranging (LiDAR), robotic total stations, and now small UAS, allow for surveying at scales that were not possible with the traditional technologies.

FAA REGULATIONS

UAS operators in both the public and private sectors must also adhere to statutory and regulatory requirements. Public aircraft operations (including UAS operations) are governed under the statutory requirements for public aircraft established in 49 USC § 40102 and § 40125. Additionally, both public and civil UAS operators may operate under the regulations promulgated by the Federal Aviation Administration. The provisions of 14 CFR part 107 apply to most operations of UAS weighing less than 55 lbs. Operators of UAS weighing greater than 55 lbs may request exemptions to the airworthiness requirements of 14 CFR part 91 pursuant to 49 USC §44807. UAS operators should also be aware of the requirements of the airspace in which they wish to fly as well as the requirements for the remote identification of unmanned aircraft. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/

Public aircraft operation is significantly limited in purpose under the statute and activities such as mapping, surveying, planning or monitoring infrastructure construction and other generalized public works activities do not qualify for public aircraft authority. These UAS activities must be carried out under the authority of part 107. All government entities qualify for operation as a civil entity and may operate under the rules of part 107. Unlike public aircraft operation, part 107 has few restrictions on operational purpose. Public aircraft operations face additional requirements. Operating in accordance with part 107 requires the remote pilots in command to have a remote pilot certificate which is done on an individual pilot basis, while public aircraft operations require additional coordination with the FAA for approval for the organization as a whole, as well as determination that the function for which the operation would occur falls within the parameters of § 40125(a)(2). Public aircraft operations also require the organization to take on additional risk and liability. Table 1 provides a comparison of the requirements for part 107 and public aircraft operations. As part 107 has evolved, there are many advantages to flying under part 107. It provides few restrictions on operational purpose, use of the Low Altitude Authorization and Notification Capability system (LAANC), less reporting requirements, and ongoing beneficial updates, which has made part 107 a choice for many State DOTs.

Safety is a crucial element of each flight and is the responsibility of the Remote Pilot in Command (RPIC). The FAA regulations for the commercial use of small UAS help mitigate risk for operations. It is the duty of the RPIC to ensure that the small UAS is in a condition for safe operation. (14 CFR § 107.15) Positive relationships with other agencies and the public to coordinate and notify those whom the operations may affect (e.g., medical helicopter flights, nearby airports, property owners) can help facilitate local awareness of recurring operations.

Table 1. Comparison of FAA Part 107 and Public Aircraft Operator

	Commercial Operations 14 CFR § 107	Public Aircraft Operator 49 U.S.C. § 40102 and § 40125
Aircraft Requirements	UAS <55 pounds	Self-certification by the public agency
Pilot Requirements	Part 107 remote pilot certificate with small UAS rating	Self-certification by the public agency
Airspace Requirements	Airspace waiver or authorization for Class B, C, D, E airspace.	Blanket Certificate of Authorization (COA) or Standard COA for Specific Airspace
Types of Operations	Visual Line of Sight, Class G Airspace, Below 400 ft above ground level (AGL)	Public Aircraft Operations (AC 00-1.1A)

Safety programs vary between agencies and involve an understanding of the nature of the work and the obstacles that are on-site. It can be beneficial to develop risk management procedures that include the following topics:

- Part 107 rules
- Airspace
- Weather
- Proximity to traffic and people
- Radio interference
- Emergency procedures
- Identification and understanding of potential site hazards before flying
- Pilot experience and proficiency

Furthermore, detailed logs, including the time of the day, weather, aircraft/sensor, and the number of construction personnel on-site, are other considerations when planning and documenting a flight.

RPIC of small UAS must be cognizant of the requirements of the airspace in which they wish to fly. When flying in controlled airspace, FAA uses the LAANC system to provide near-real time approval from Air Traffic Control (ATC) at many airports where appropriate. The FAA offers extensive resources and information to help RPICs determine which laws, rules, and regulations apply to a particular small UAS operation. For more information, see https://www.faa.gov/uas/.

UAS AIRCRAFT PLATFORMS

A variety of factors should be considered when investing in small UAS for construction quantity estimation. Three major types of small UAS are available based on the type of aircraft: namely multi-rotor, fixed-wing, and helicopters (see Table 2). Each type of aircraft has its strengths and weaknesses depending on the applications. Fixed-wing can be the most advantageous to cover large areas efficiently, provided the operator obtains a waiver from the FAA for beyond visual line of sight operations.

Helicopters tend to be larger aircraft (some even outside the small UAS definition in 14 CFR § 107.3), often gas-powered with heavier lift. For construction quantity estimation applications, multi-rotor aircraft are typically preferred because they can take off and land vertically, easily maneuver under challenging environments, and hover in place. Multi-rotor aircraft are generally limited to 25-30 minutes of flight time. Depending on the size of the area that is being measured, multiple batteries may be involved.

Table 2. Aircraft Platforms Strengths and Weaknesses

Multi-Rotor UAS	
Strengths	**Weaknesses**
Vertical take-off and landing and flexibility on take-off and landing sites	Battery life
Hover in place	Generally lower payload capacity
Easy to fly	Lower endurance than fixed-wing
Maneuverable	Expensive repairs
Lower cost	
Ability to change camera angles	Smaller payload capacity
Precision maneuvering	
Fixed-Wing	
Long endurance	Cannot hover unless VTOL
Aerodynamically efficient	Can be target for birds-of-prey
Cover large areas more efficiently	Need large take-off and landing zones
Helicopters	
Carry larger payloads (gas-powered aircraft)	Difficult to fly manually
	Higher cost

REMOTE SENSING TECHNOLOGIES

Remote sensing technologies for small UAS include high-resolution red, green, blue (RGB) cameras, thermal cameras, ultrasonic sensors, and LiDAR. The decision to use images or LiDAR data to calculate construction quantities depends on the type of construction work being measured, project sites, the ability to set up control points, and the project budget.

RGB cameras are equipped with charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) sensors, typically with a Bayer array to produce red, green, blue (natural color), and these are generally higher-end cameras (DSLR or mirrorless). High-resolution RGB visual camera sensors come in various configurations and specifications, which should be evaluated when choosing a small UAS for construction quantity estimation. Data collection using RGB cameras can be enhanced by having a fundamental knowledge of:

- ISO (standard industry scale for measuring the sensitivity of image sensor to light)
- Aperture (size of the opening; given by f-stop, as aperture increases, f-numbers decrease)
- Shutter speed (controls how long image sensor is exposed to light)

While automated settings can be helpful, they can also be detrimental in areas with complex or changing lighting conditions. Proper exposure affects image quality, amount of noise, and motion blur. The quality of these images affects the accuracy of construction quantity estimates because they are processed using structure from motion (SfM) photogrammetry software to extract 3D geometric information from two-dimensional (2D) images.

SfM is a photogrammetric range imaging technique for estimating 3D structures from 2D image sequences to create multiple data outputs such as ortho-imagery, 3D mesh, Digital Elevation Models (DEM), or point clouds. SfM is an increasingly popular approach due to its advantages in cost, computation, and ease of use. (Carrivick et al. 2016) It has been used in several engineering and construction applications, including earthwork volume calculations and progress monitoring. Several SfM software packages are available in the market.

The main SfM steps include:

- Automated identification of matching features (key points) in multiple images

- Feature tracking from image to image allowing to estimate initial camera positions and object coordinates
- Iterative least-squares fit process to minimize errors
- Development of dense point clouds using multi-view stereo algorithm (see Figure 1)
- Identification of ground control points (GCPs)

SfM is gaining momentum and acceptance as a tool for the volumetric calculations that are necessary for construction quantity estimation (Mora et al., 2019). The number and location of GCPs used for SfM can affect the accuracy of the quantity estimates. As a result, it can be beneficial to establish five or more GCPs strategically across the site to avoid undesirable results. In addition to GCPs, random checkpoints are suggested to establish the accuracy of the project.

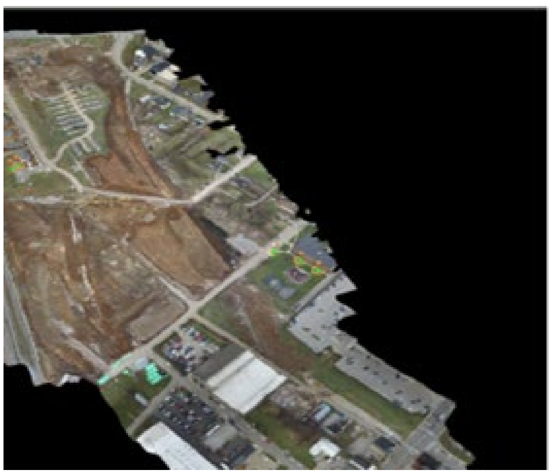


Figure 1. Dense point cloud developed using SfM (Image courtesy of Xi Wang, UKY)

LiDAR is an active remote sensing technique that uses electromagnetic energy (laser). Laser pulses transmitted by the LiDAR system travel down toward the Earth's surface, reflect off a surface patch, and return to the airborne sensor where the roundtrip travel time is measured. LiDAR scanners emit pulses of light (at speeds ranging from thousands to millions of points per second) to acquire X, Y, Z (3D) positions of points within an area of interest, producing a point cloud. Because LiDAR is an active sensor, solar illumination (e.g., clouds, low sun angle) does not affect the measurements/data collection. LiDAR sensors can be classified as survey (5 to 10-millimeter accuracy) or mapping grade (1 to 3-centimeter accuracy). For quantity calculation, a survey-grade LiDAR is necessary to obtain accurate results.

When metric information is needed (i.e., measuring in the photograph), GCPs are helpful to provide accurate, repeatable results. GCPs are image-identifiable points whose coordinates have been obtained by a field survey—typically using real-time kinematic (RTK) global navigation satellite systems (GNSS). GCP acquisition can be a big part of the time and cost of the project when required (10 to 50 percent of total project costs). Survey-grade (i.e., carrier-phase, multi-frequency, multi-constellation) GNSS on the small UAS that can support RTK or post-processing kinematics (PPK) can reduce some of the GCP demands.

Although UAS-SfM and UAS-LiDAR techniques typically provide comparable data accuracies (with some differences, as a function of terrain and ground cover type), the application of UAS-SfM is generally less expensive, imposes less stringent standards for the remote aircraft, needs less expert knowledge and training to operate, and yields higher data densities. Therefore, a general recommendation in the industry is that SfM processing should be the default platform used for typical small scale, less than 2 square kilometers, high-density topographic mapping applications based on its low cost, attainable accuracy, and usability (Simpson 2018). Simpson found that disadvantages associated with SfM include moving objects, dense foliage, and blurry imagery. However, UAS-LiDAR are suggested when any of the following conditions apply:

- The Area of Interest (AOI) has homogenous surface texture over a large area
- Data acquisition through a thick canopy is involved
- Poor light conditions (e.g., extreme amounts of shadowing throughout the AOI, data collection at night) are anticipated
- Surface characteristics derived from intensity returns are needed
- The AOI contains substantial vertical gradients
- A large amount of tall (relative to flying height) vertical obstructions are located throughout the AOI

Regardless of the mapping system being used, a thorough understanding of the acquisition platform and processing procedures may contribute to accurate final products for quantity estimation.

FLIGHT OPERATIONS

Pre-Flight Planning

Flight planning should include a thorough assessment of the site of interest to:

1) Identify any obstacles (e.g., powerlines, tall buildings, cell towers)
2) Choose take-off and landing zones
3) Determine if there is radio interference

4) Address privacy issues and coordinate with affected parties (e.g., airports, site personnel, medical/military helicopters in the vicinity, property owners, permits)
5) Obtain a COA/waiver if needed for operation

Additionally, the RPIC must complete a preflight familiarization, inspection, and other actions prior to beginning flight operations (14 CFR § 107.49) for part 107 small UAS operations.

Next, data collection goals should be established, which involves selecting the appropriate airframe and sensor combination and determining the number and distribution of GCPs based on the project specifications. SfM software enables processing of the data with or without geo-locations; however, accurate and well-distributed GCPs can improve the global accuracy of the project.

Once project specifications are established, the flight plan to meet these specifications can be designed. For example, increasing the flying height will commonly decrease the resolution of the imagery. Flight parameters, such as image overlay settings, camera angle for data collection, and flight line patterns, can be determined using the flight software. Commercial small UAS typically come with their own flight planning software packages that can be operated either using a remote controller or with brand-specific applications available for smartphones. Third-party applications are also available that may provide additional functionality, including terrain-following or the ability for modular flights or advanced operations.

After the flight is planned or concurrently with flight planning, if needed, GCPs should be established with an RTK GNSS unit or total station. GCP targets should be the right size and shape and made of materials (not too shiny) so that they are visible and easily identifiable in the collected images. Additionally, they should be evenly distributed over the AOI, as illustrated in Figure 2. If GCPs are not evenly distributed (i.e., if GCPs are all at the same location, all on one side, or the very edge of the area), georeferencing could be unbalanced, making GCPs unreliable. (Wang 2018) This may also lead to a warped 3D surface, as illustrated in Figure 3.

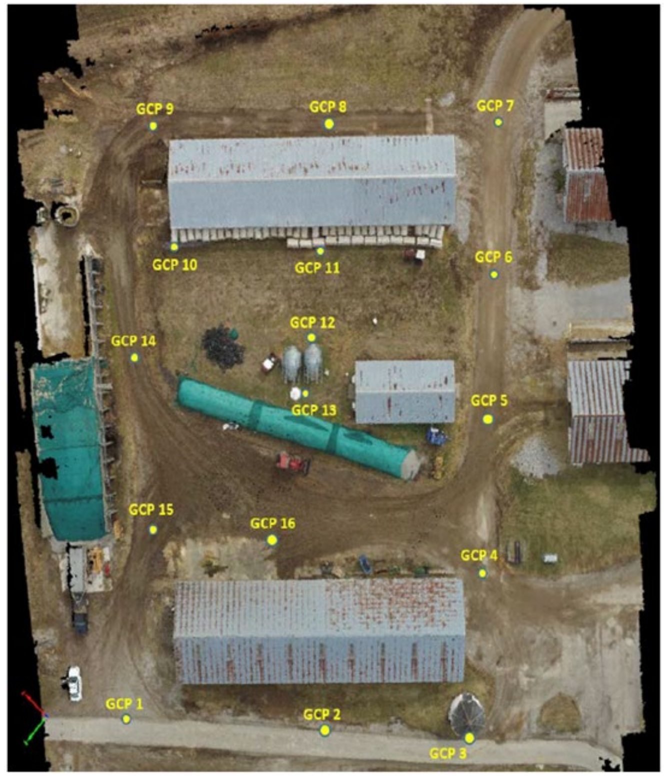


Figure 2. Distribution of GCPs (Image courtesy of Xi Wang, UKY)

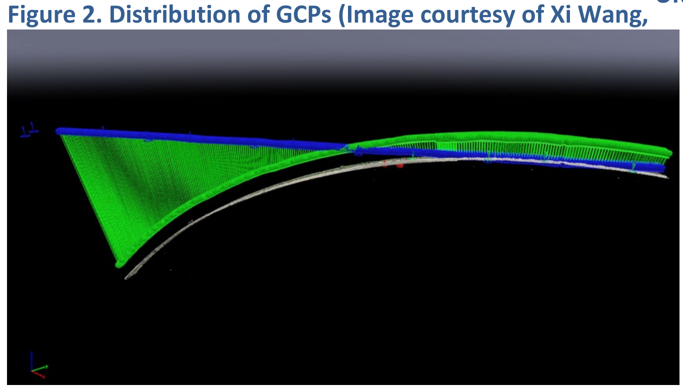


Figure 3. Warping of model from improper layout of GCPs (Image courtesy of Utah DOT)

Mission Operation

Final coordination prior to the flight includes a final site review, examination of primary/alternate take-off and landing locations, and coordination with pertinent parties (e.g., medical/military helicopters, ATC, and property owners). In addition, the airframe should be inspected thoroughly, and the flight software should be set up before the flight.

Flight software setup involves determining flight lines and sensor (RGB camera or LiDAR) settings. GCPs should not be established on the edges of the flight area, and overlap settings (front and side overlap), and the orientation for best data capture should be determined. The flight altitude for best Ground Sample Distance (GSD) should also be determined because this affects the resolution of the images captured, ultimately affecting the accuracy of quantity estimates. GSD is the distance between two consecutive pixel centers measured on the ground. The larger the value of GSD, the lower the image's spatial resolution and the less visible details. It is helpful to consider the balance between spatial resolution and area covered in selecting flight altitude. Higher spatial resolution may result in higher image quality, but the flight duration can be longer. Because of the battery life limitations of the small UAS, the flight may need to be fragmented into multiple flights. Under different flight conditions, the image quality cannot be guaranteed because of variations in illumination, saturated images, or the appearance of shadows. Therefore, flight altitude is one of the most influential factors affecting the quality of the end product. Planning flight lines for the object is important to achieve accurate results. For complex objects, a crosshatch flight line (Figure 4) may be needed to adequately capture all angles of the site; a simple linear style pattern (Figure 5) may be sufficient for simple geometry.

Figure 4. Crosshatch flight line pattern (Image courtesy of WSP USA)

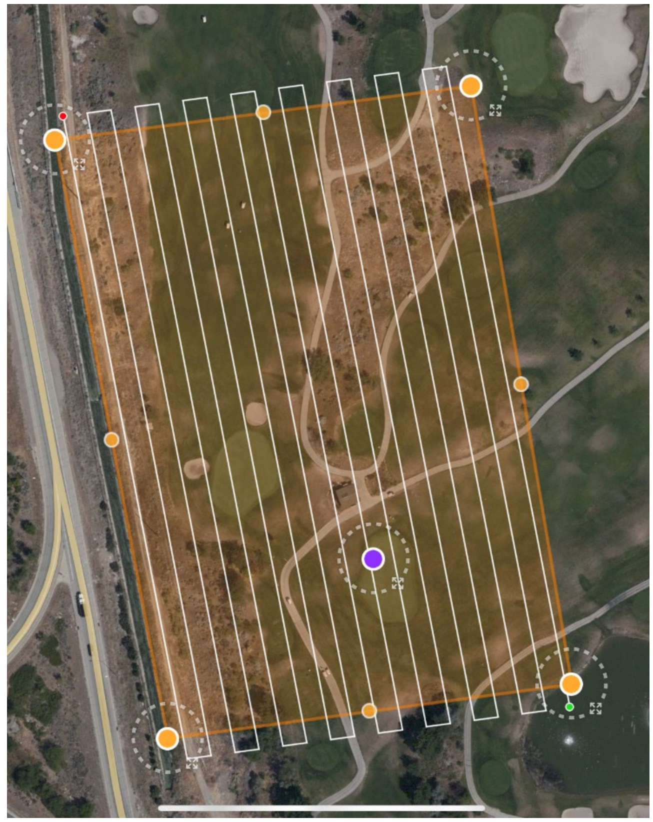


Figure 5. Linear flight line pattern (Image courtesy of WSP USA)

For RGB cameras, as described under Remote Sensing Technologies (above), the way ISO, aperture, and shutter speed work together affect image quality; thus, these variables should be set up carefully. For example, motion blur may occur if the small UAS are flying too fast with respect to the shutter speed. Motion blur is the distance traveled by the small UAS camera over a single exposure. Typically, motion blur should not be greater than 1 x GSD, where GSD is the distance on the ground for every two adjacent pixels in the image. It is difficult to completely eliminate motion blur; however, it is possible to reduce it considerably by:

- Reducing flight speed
- Increasing shutter speed
- Increasing GSD by increasing the mission altitude

Poor lighting conditions also may be experienced during the flight, which can be overcome with:

- Proper exposure
- Illuminance (brightness)
- Exposure time

To maintain proper exposure, shutter speed (exposure time) can be changed by adjusting the f-stop setting (aperture area). Aperture refers to the opening of a lens diaphragm through which light passes; a higher aperture (e.g., f/16) means less light enters the camera. Similarly, a lower aperture (e.g., 1.8) means more light enters the camera, which is better for low-light scenarios. Flight crews should have a basic knowledge of photography to be prepared for multiple lighting conditions. If the small UAS are equipped with a LiDAR sensor, the density and the optimal overlap between flight lines should be set up to ensure that the project goals are met.

Post-Flight Inspection

At the end of data collection, before leaving the site, the airframe should be inspected to ensure there is no damage and that all the sensors are working. If sensors are not working, they should be repaired or replaced.

The collected data should be reviewed to make sure that it meets the project requirements and is of sufficient quality for the data goals. If the images are blurry or have abnormalities, the flight may need to be repeated. Problems are easier to remediate while still on-site. It is also important to back up the data, either to a computer or a cloud-based platform.

Before leaving the site, the flight crew should perform coordination calls with the pertinent parties (e.g., medical/military helicopters, ATC, property owners). These coordination calls should also occur prior to commencing flight operations and after the flight operations have commenced.

Data Post-Processing

The first step in data post-processing involves cleaning the data of blurry images and removing noise if LiDAR was used as the sensor of choice. Depending on the sensor (RGB camera or LiDAR) used, an appropriate software package should be selected and used for data processing.

If RGB cameras are used, the SfM procedure described under Remote Sensing Technologies (above) should be applied to obtain the 3D information used to estimate construction quantities. The final deliverables can be digital terrain models (DTMs), ortho-images, 3D mesh, or point clouds. If LiDAR is used, the data processing workflow involves processing the flight trajectory to determine the geo-location of LiDAR data, followed by flight line alignment to increase relative accuracy. Next, the point cloud can be colorized if using co-acquired imagery (this is an optional step). The final product is generated in the form of DEM, DSM, or classified point cloud, which can directly be used for quantity estimation.

Finally, a comprehensive data management plan, including data backup, retention, quality control, and delivery can help ensure that the collected data and post-processing products such as point clouds and ortho-imagery are checked for accuracy, backed up, and retained for the agency's records.

Data Management

UAS data collection produces a considerable amount of information that needs an efficient management plan to allow for the dissemination between organizations. A data management plan should be developed and followed early in the process to achieve the best results and include all phases of construction. Having a process and framework for data management can create a repeatable and reliable system that are key elements for success, as illustrated in Figure 6.

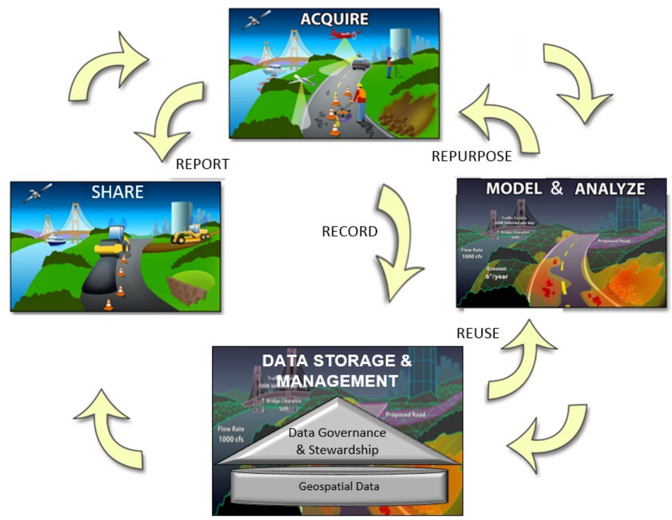


Figure 6. Data Management Life Cycle (Mallela, et al. 2018)

The data management plan should include:

- Goals and purpose for the data
- Considerations on the proper tool to acquire the data and achieve the required goals
- Hardware and plans for processing the data
- Means for quality control and assurance
- Plan for dissemination, storage, and management
- Data sharing

As digital delivery becomes more prevalent, small UAS can help play a key role in data collection. Dynamically incorporating data into a management plan can assist with:

- Partnering and collaboration between parties on construction projects.
- Helping to reduce the likelihood of errors through higher density data collection.
- Increasing return on investment from faster collection times.
- Helping to facilitate progress reporting through 3D models throughout the life of the project.
- Enabling additional tools to supplement conventional technologies.

CONSTRUCTION USE CASES

Pre-Construction

Pre-construction practice sets the foundation for any successful construction project. Early in the pre-construction phase, it can be time-consuming to gather critical details about topography. Traditional ground surveying can take days to collect data about a new site. The data processing and delivery of a report can take weeks, depending on the size of the project site. Small UAS can capture existing conditions or verify survey measurements or both prior to initiating a construction project. Existing conditions can be evaluated directly from images, and for survey verification, images can be processed into a 3D point cloud using SfM technique. Multiple DEMs or point clouds can be compared to determine the accuracy of the existing topography prior to construction as illustrated in Figure 7. Verifying the surfaces before construction is an added benefit that can improve design quality and prevent change orders because the design is based on accurate 3D measurements. As the industry moves more toward digital delivery over traditional plan sets, higher quality data are important. Information collected via small UAS can allow for more precise bidding and feasible and realistic expectations for design elements and timelines. A bid that overestimates the amount of earth to be moved would inflate the bid cost, and the contractor would likely lose the project. Alternatively, a bid that underestimates the amount of earth to be moved could be attractive but would cause the contractor to lose money later. Having access to dense, accurate information about existing conditions can facilitate transparency and build better relationships.

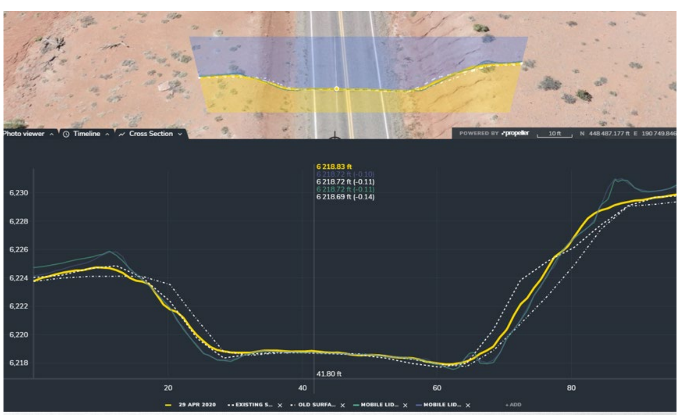


Figure 7. Existing topography comparison of multiple surfaces for verification (Image courtesy of Utah DOT)

Construction

Small UAS can be suitable for documenting different phases of a construction project, as illustrated in Figure 7. As noted above, accurate and reliable estimates of earthwork quantities is important to both State agencies and contractors because they are used for project payments and digital inspection methods. Developing an accurate bid or project schedule also depends on accurate estimates.

Earthwork involves moving massive quantities of soil or rock. The goal is to reconfigure the topography of a construction site to meet the project owner's design requirements. Most earthwork operations are executed in the early stage of the construction process, meaning that the earthwork progress controls the overall project schedule.

During construction, small UAS can be used to monitor earthwork quantities, including subgrade and final surface quantities (Figure 8), linear elements such as fence, curb and gutter, drainage elements, and structures. At the end of the construction phase, small UAS can be used to document as-built conditions.

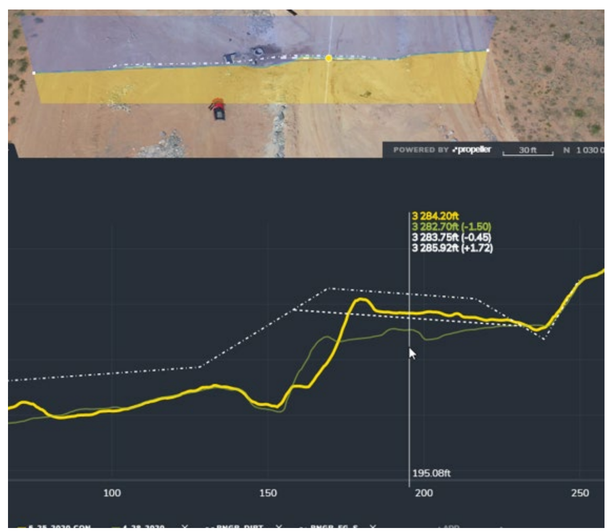


Figure 8. Construction phase cross-section views (Image courtesy of Utah DOT)

SfM is one processing tool that can be a beneficial for 3D quantity measurements. (Simpson 2018) When using SfM, the quality of the 3D models depends on the number of images, the percentage of overlap between images, and tie points. The use of GCPs is an effective method to further improve the accuracy of 3D models when using SfM. (Wang 2018) GCPs are typically measured using highly accurate GNSS units in the AOI. Furthermore, because these points are measured using GNSS units, they can be used to determine the scale, orientation, and positions of the results.

Several studies evaluated the impact of DEM resolution on earthwork calculations (Siebert and Teizer 2014, Tobias 2020). DEMs are commonly used during the project planning phase and directly affect earthwork estimation and construction costs. DEMs generated using small UAS and GNSS were compared to determine the impact of the resolution on earthwork calculations using the data obtained from different road construction projects. The variance was found to be 1-2 percent in volume, which is within acceptable tolerances. Wang (2018) assessed the application of small UAS in measuring earthwork quantities, including stockpiles (Figure 9) and trench volumes (Figure 10), and the accuracy of the results they obtained was comparable to those obtained using traditional surveying methods. Utah DOT reports that small UAS and SfM photogrammetry technologies have been suitable and helpful in some construction quantity estimations.

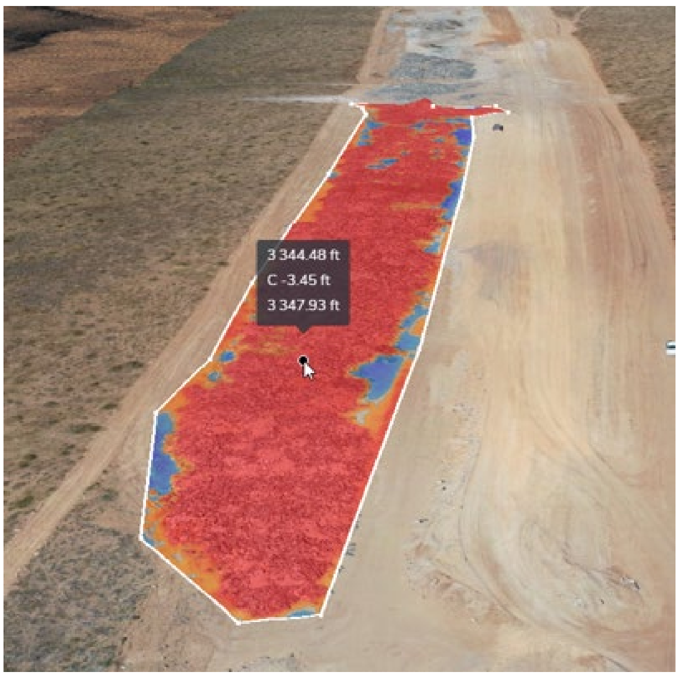


Figure 9. Construction quantity calculation (Image courtesy of Utah DOT)

UAS may offer a quicker and more cost-efficient way of measuring stockpile volumes. A study by Mora et al. found that compared to terrestrial LiDAR, the average difference observed in the vertical component was 2 millimeters with a standard deviation of 31 millimeters (Mora et al., 2019).

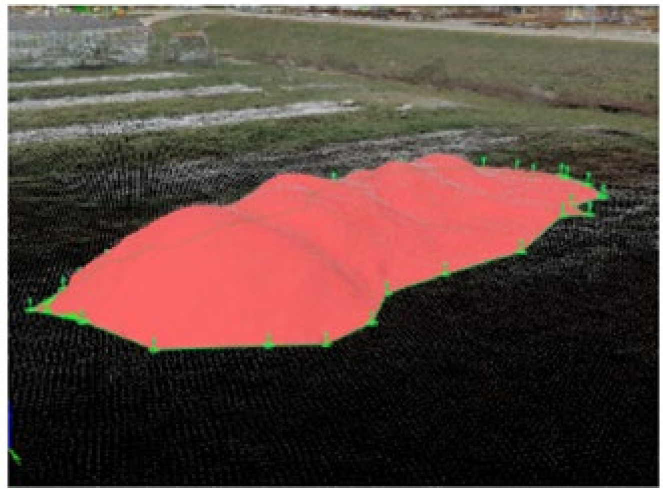


Figure 10a. Stockpile volume drawn in point cloud (Image courtesy of Xi Wang, UKY)

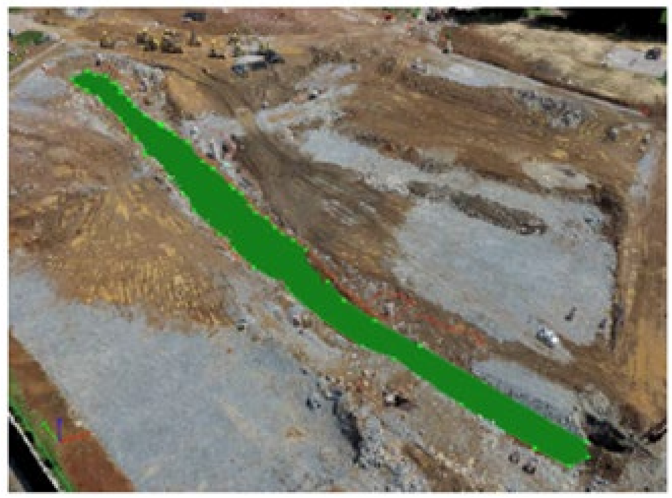


Figure 10b. Trench volume drawn in point cloud (Image courtesy of Xi Wang, UKY)

Post-Construction

At the end of the construction phase, the responsibility of the property often passes from the contractor to the owner or manager through contract documents. This process involves preparing handover documents, taking measurements to prepare as-built plans, and verifying quantities for final payment. Compared to traditional survey measurements, small UAS can help rapidly measure and verify quantities and develop final as-built documents. Traditional survey methods involve manual measurements of ground data points, which increases the amount of time needed for data collection while also increasing the project costs. Furthermore, using small UAS for data collection from larger, more complex sites does not necessarily require additional time.

CONCLUSION

The affordability and capabilities of small UAS and SfM software have improved over the last few years. Small

UAS technology can be an effective way to provide accurate and usable data (Zhou 2018). Mapping with small UAS can provide vital information regarding the quantity of soil removed from borrow pits by measuring clay and topsoil volumes separately, determining the distance soil is hauled, and verifying the compaction rate on the finished project. Small UAS and SfM software for construction quantity estimation can be purchased from multiple suppliers for between $2,000 and $35,000, depending on the sensors and technology. Small UAS can be an effective tool for estimating quantities for transportation construction. They can reduce the time needed for such calculations, improve efficiency, decrease costs, and improve overall project safety (Li & Liu, 2019). According to American Society for Photogrammetry and Remote Sensing (ASPRS) published standards[1], accepted practice, and literature, the measurement errors are in an acceptable range when parameters are under control. In addition, the UAS technique demonstrates its advantages in balancing between accuracy and efficiency compared with conventional earthwork volume measurement methods (Mora et al., 2019).

REFERENCES

AASHTO (2019) Mission Control Transportation TV Special Reporthttps://www.transportation.org/wp-content/uploads/2019/05/MissionControl_Drones3.pdf

Carrivick, J., Smith, M., and Quincey, M. (2016). Structure from Motion in the Geosciences, ISBN: 978-1-118-89584-9

Li, Yan and Liu, Chunlu. (2018). Applications of multirotor drone technologies in construction management. International Journal of Construction Management. 19. 1-12. 10.1080/15623599.2018.1452101.

Mallela, J., Mitchell, A., Gustafson, J., Olsen, M., Parrish, C., Gillins, D., Kumpula, M., and Roe, G. (2018). Effective Use of Geospatial Tools in Highway Construction, August 2018 - FHWA-HIF-19-089. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/19089/

Mora, O. E., Suleiman, A., Chen, J., Pluta, D., Okubo, M. H., and Josenhans, R. (2019). Comparing sUAS Photogrammetrically Derived Point Clouds with GNSS Measurements and Terrestrial Laser Scanning for Topographic Mapping. Drones 2019, Vol. 3, Page 64, 3(3), 64. https://doi.org/10.3390/DRONES3030064

Reed, J. (2015). Land Surveying Transforms Along with Technology. The Gazette. https://www.thegazette.com/subject/news/business/land-surveyingtransforms-along-with-technology-20150307

Siebert, S. and Teizer, J. (2014). Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system. Automation in Construction, 41, 1-14.

Simpson, C.H. (2018). A Multivariate Comparison of Drone-Based Structure from Motion and Drone-Based Lidar for Dense Topographic Mapping Applications. Oregon State University.

Tobias, M. (2020). 2019 Technology Trends in the Construction Industry. https://www.ny-engineers.com/blog/2019-technology-trends-in-the-construction-industry

Wang, X. (2018). Assessing the Application of the Unmanned Aerial Systems (UAS) In Earthwork Volume Measurement. Theses and Dissertations--Civil Engineering.

Willis, F. (2013). How Can Drones Transform Surveying? Point of Beginning (POB) Magazine. https://www.ny-engineers.com/blog/2019-technology-trends-in-the-construction-industry

Zhou, S. and Gheisari, M. (2018). Unmanned Aerial System Applications in Construction: A Systematic Review, Construction Innovation, Vol. 18 No. 4, pp. 453–468. https://doi.org/10.1108/CI-02-2018-0010

ONLINE RESOURCES

AASHTO Mission Control 2019 UAS/Drone Survey of All 50 State DOTs. https://www.transportation.org/wp-content/uploads/2019/05/MissionControl_Drones3.pdf

Electronic Code of Federal Regulations Title 14: Aeronautics and Space, Subchapter F, Part 107—Small Unmanned Aircraft Systems. https://www.ecfr.gov/cgi-bin/text-idx?node=pt14.2.107&rgn=div5

Federal Aviation Administration (FAA) Unmanned Aircraft Systems (UAS). https://www.faa.gov/uas/

Federal Highway Administration (FHWA) Unmanned Aerial Systems (UAS). https://www.fhwa.dot.gov/uas/

FHWA Center for Accelerating Innovation Every-Day Counts-5 (EDC-5): Unmanned Aerial Systems (UAS). https://www.fhwa.dot.gov/innovation/everydaycounts/edc_5/uas.cfm

[1] The use of ASPRS standards is not a Federal requirement.

Tech Brief

USE OF SMALL UNMANNED AERIAL SYSTEMS FOR RETAINING WALL INSPECTIONS

Introduction

Like every class of assets, retaining walls need to be inspected and assessed periodically to analyze their performance and identify issues to prevent future failure (Gerber, 2012). State Departments of Transportation (State DOTs) must maintain asset management programs, which include the inspection of retaining walls (23 U.S.C. 119 (d)(2)(D)). Many of the structures are constructed in challenging site conditions, including mountainous terrain, soft ground, and sites that are not easily accessible (Brutus and Tauber, 2009).

Key Takeaways

- UAS can assist to access hard-to-reach areas.
- UAS have been used to find defects that could have led to a failure in the structure.
- UAS may assist to provide a safer infrastructure system through more frequent inspections.

The use of specially trained personnel using ropes for accessing steep, highly exposed wall faces may increase the risk for the operation and be cost-prohibitive. Additional hazards regarding wildlife, insects, and poisonous plants can also be a safety factor for inspectors (DeMarco et al., 2010). Unmanned aircraft systems (UAS) have become synonymous with the ability to collect data in challenging site conditions. They can be a helpful tool for retaining wall inspections, condition assessments, and ratings.

Many State DOTs are using UAS for infrastructure inspections, including retaining walls. The ability to deploy UAS without affecting traffic flow can help State DOTs carry out inspection duties without inconveniencing the traveling public. The ability to provide a detailed three-dimensional (3D) model or point cloud may also be advantageous to provide an overall assessment for movement and stability of the site. With advances in advanced analytics, UAS data may also be incorporated into artificial intelligence and machine learning algorithms to analyze and create prediction models for the life cycle of retaining walls.

UAS for Retaining Wall Inspections

Figure 1. MnDOT Retaining Wall Inspection Using UAS (Photo Courtesy MnDOT)

Using UAS for retaining wall inspections can supplement existing tools for condition-based inventory systems (Figure 1). The assessment of the condition of a retaining wall is the most critical part of its inspection record and serves as the basis for decisions about maintenance, repair, the frequency of future inspections, and even possible replacement (Brutus and Tauber, 2009).

Understanding the goals for the inspection and the environment where the retaining wall is located is the first step when considering which aircraft platform and sensor is best suited for the operation. UAS may be beneficial in data collection efforts for most of the earth-retaining structure (ERS) attributes identified in Figure 2. UAS may also increase the efficiency of the time on-site and the return on investment of the equipment. The ability to process UAS data to create 3D models and georeferenced imagery can be beneficial for many workflows, while the ability to import data collected from UAS into various software provides the means to accurately measure, sketch, and have detailed documentation for the inspection team. Some considerations for UAS collection methods for inspecting retaining walls are illustrated in Figure 3.

Figure 2. ERS Condition Attributes (Source: Brutus and Tauber, 2009)

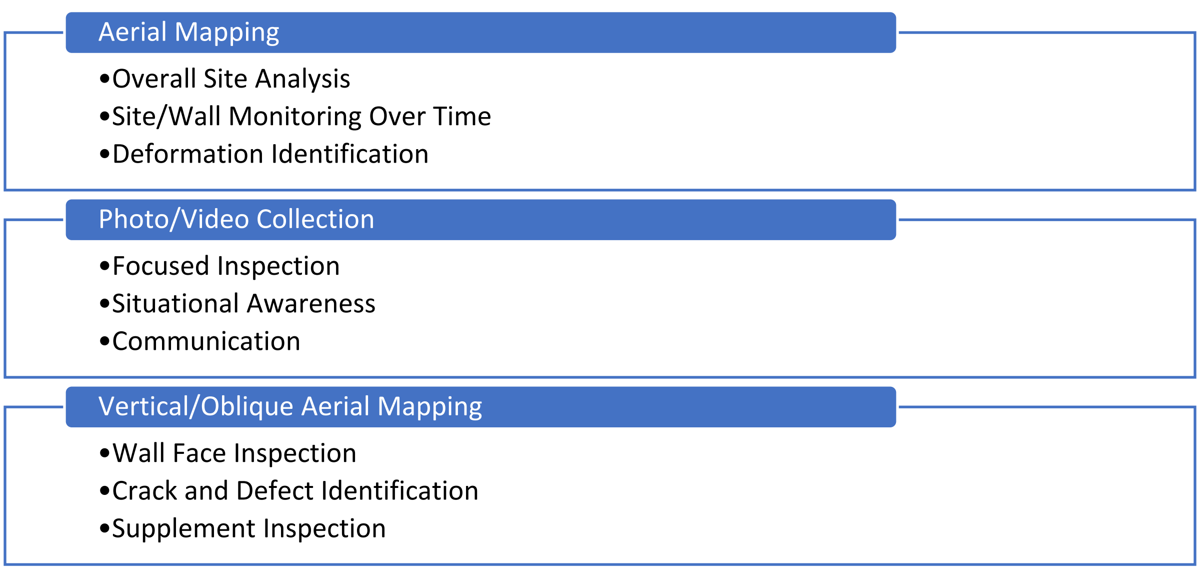


Figure 3. Considerations for UAS Collection Methods for Retaining Walls (Source: FHWA)

Aerial Mapping

Aerial mapping may be helpful for overall site analysis or to monitor a site over time. UAS may be a viable solution for surveying a more extensive site area to provide additional information for geotechnical investigations that are difficult to monitor using conventional methods. Aerial maps and 3D point clouds provide a base model to analyze subsequent data to better understand the site as a whole. As an example, the California DOT (CalTrans) Steep Terrain Group used UAS to find a large hole in the crib wall supporting the toe of the slope below the northern abutment of the Lime Kiln Bridge in Big Sur and initiated emergency repairs, as illustrated in Figure 4.

Figure 4. Lime Kiln Bridge on Highway 1 on the Big Sur Coast (Photo courtesy of Caltrans Steep Terrain UAS Group)

Boreholes provide specific data about the environment, but having supplemental data from UAS to provide an overall understanding of the entire site and boundaries of the wall may also be helpful. Supplementing the inspection by combining UAS and conventional data collection methods may provide additional data to better understand the complex environment surrounding the wall and failure points that may be present in the surrounding topography.

A variety of sensors can be used for the aerial mapping of the walls, but red, green, blue (RGB) cameras or Light Detection and Ranging (LiDAR) are typically used. A passive (RGB or traditional) camera will often be processed using Structure for Motion (SfM) to create a 3D model or point cloud. Passive (RGB) cameras are available at a lower cost and are beneficial for use in environments with minimal vegetation or when including the vegetation in the point cloud will not degrade the data requirements. In situations when a ground-level survey is needed in high vegetation areas, a UAS LiDAR scanner with multiple returns can be helpful because it can penetrate through vegetation. Additionally, when using UAS for aerial mapping, it may be beneficial to incorporate ground control points (GCP) and real-time kinematic (RTK) or post-processing kinematic (PPK) to improve data accuracy and accurately align subsequent flights. Establishing permanent control or reference points outside the walls' boundaries can provide a durable reference point for quality control and establish GCPs for future flights. If the GCPs for the aerial mapping are all established in an area with ground movement, it may help to verify their accuracy prior to flight to determine if they have moved since the last operation. The coordinates will need to be adjusted to prevent errors introduced into the data sets when processing if the points have moved.

Photo and Video

Using UAS for photo and video collection may be helpful due to their ability to rapidly access hard-to-reach areas. Workers can perform the work from a safe location while collecting the data. In addition, using UAS instead of ropes or ladders can substantially increase productivity and improve safety while also providing a collection of higher quality georeferenced data (Lovelace and Wells, 2018).

Vertical Mapping

Using UAS for vertical mapping typically requires an aircraft with the ability to hover (e.g., rotorcraft) in addition to a moveable gimbal, which allows the camera to be rotated perpendicular to the face of the wall. Without these features, it can be difficult to see all the aspects of the wall face. For example, mapping from a nadir direction (directly below, perpendicular to the aircraft) can create anomalies or fail to provide data on vertical faces, as illustrated in red on the missing data on cliff faces in Figure 5 because the vertical faces were obscured from a top-down angle. If the camera is positioned slightly oblique, it can capture more of the surface area. Figure 6 illustrates this phenomenon more simply. The oblique angle can "see" the vertical face of the wall, while the nadir angle obscures it.

Both active (e.g., LiDAR) and passive (e.g., RGB) sensors may be helpful for vertical mapping. Depending on the material or texture of the wall, LiDAR may be favorable if too much noise or ambiguity is introduced through SfM processing. Similarities in the texture of the material may prove difficult for photogrammetry to decipher, leading to ambiguities that create additional data noise. Selecting a quality camera or sensor may help to improve the data quality and reduce data noise when using an RGB camera. For example, a smooth surface may look rough and not uniform if the data set has a high value of noise or ambiguity in an SfM point cloud. For identification of defects and monitoring over time, it is often beneficial to incorporate aerial imagery and point clouds to provide detailed imagery and 3D models to analyze.

Figure 5. Missing Data with nadir angle 3D mapping (Photo courtesy of Utah DOT)

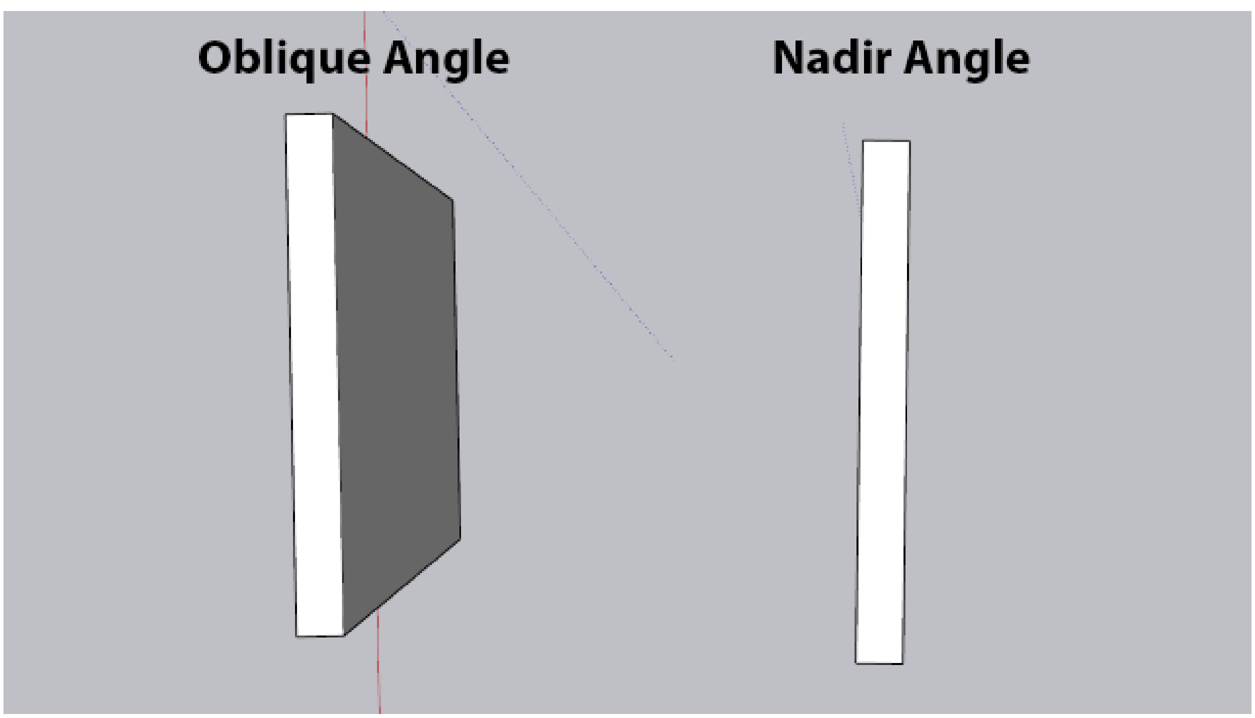


Figure 6. Oblique and nadir angles for walls (Source: WSP)

Caltrans Steep Terrain UAS Group used UAS to create a 3D model to capture and quantify the damage created from the 2020 Meyers Fire, which burned the slopes and damaged the wood lagging retaining walls of highway infrastructure, as illustrated in Figure 7 and Figure 8.

Figure 7. 3D model of post fire response north of Jenner, California (Photo courtesy of Caltrans Steep Terrain UAS Group)

Figure 8. 3D model of post fire response north of Jenner, California (Photo courtesy of Caltrans Steep Terrain UAS Group).

Data Collection Planning

When using UAS for retaining wall inspections, understanding the capabilities of the aircraft, data goals, and deliverables can be important. Having a comprehensive data collection plan before any operation can help optimize each step of the process.

FAA Regulations

UAS operators in both the public and private sectors must also adhere to statutory and regulatory requirements. Public aircraft operations (including UAS operations) are governed under the statutory requirements for public aircraft established in 49 USC § 40102 and § 40125. Additionally, both public and civil UAS operators may operate under the regulations promulgated by the Federal Aviation Administration. The provisions of 14 CFR part 107 apply to most operations of UAS weighing less than 55 lbs. Operators of UAS weighing greater than 55 lbs may request exemptions to the airworthiness requirements of 14 CFR part 91 pursuant to 49 USC §44807. UAS operators should also be aware of the requirements of the airspace in which they wish to fly as well as the requirements for the remote identification of unmanned aircraft. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/.

UAS Sensor Considerations

For retaining wall inspections, a quality RGB camera may prove sufficient to gather photos and videos and create point clouds in combination with SfM. For deeper analysis, it may be helpful to use an infrared or thermal camera to see temperature differentials in the wall and surrounding topography, which may help pinpoint issues caused by water. A multispectral camera may prove helpful in gauging the effect of vegetation mitigation or analyzing the surrounding area because it can see additional wavelengths of various spectral regions to interpret physical plant conditions. Multispectral cameras can offer insight on where water may be more prevalent in the ground due to healthy plant growth and to monitor noxious weed mitigation efforts. LiDAR can be useful in areas where lighting conditions do not favor an RGB camera or vegetation is present, and a base map of the bare ground is needed to understand the topography better when assessing sites for movement. Table 1 provides a quick reference guide for sensors and their applications.

Table 1. UAS Sensors

UAS Sensors for Retaining Wall Inspections	
Sensor	**Applications**
RGB camera (fixed focal length and zoom lenses)	Still photos Videos Aerial imagery and mapping
Infrared or thermal	Thermographic analysis Identification of water seepages
Multispectral	Near infrared and short-wave infrared analysis
LiDAR	Detailed 3D mapping with vegetation or poor lighting conditions

Ground Control or Reference Points

Figure 9. GCPs placement (Image courtesy of UDOT)

Ground Control Points (GCPs) may be helpful when absolute accuracy for a map of a retaining wall and its surrounding terrain is necessary for creating orthomosaics and point clouds. GCPs may also prove beneficial when mapping and monitoring a site over time to understand changes in movement across the site. Without GCPs, it may be more difficult to decipher movements in the topography versus errors in the data. It may also be advantageous to create at least two GCPs outside the movement area when using them for monitoring over time. (Figure 9) If all GCPs are located inside the movement area, and the site is moving uniformly, it may be difficult to assess actual movement. Having GCPs outside the reference area can also provide an outside reference to check the internal points for verification, which allows for better site assessment. For vertical mapping, reference points on the wall that act as GCPs can help monitor movement and verify the accuracy of the data. They may also prove helpful for SfM to help reduce data noise or geometric inaccuracies and improve the accuracy of the 3D model solution during processing when the texture and/or features of the wall are similar. The reference points or GCPs should have a high contrast of color so they stand out from the existing surfaces for easier identification in the software (James et al., 2017).

Data Collection and Data Processing

UAS flights for retaining wall inspections may require multiple operations to capture the necessary data of the structure itself and its surrounding area. Consistent flight lines and adequate overlap is key to producing quality data for analysis. Retaining walls are often located in difficult terrain with varying topography. Automated mapping software may assist with ensuring the necessary overlap and consistency in uneven terrain as shown in Figure 10.

Figure 10. Automated mapping software

When crews are new to using UAS for retaining wall inspections, manually analyzing raw photos or videos may be a first step to increasing productivity or safely accessing hard-to-reach retaining walls. However, data processing that creates 3D models, point clouds, and orthomosaics can provide additional value. Minnesota DOT was able to use UAS to collect data and process it to create the colorized 3D point cloud of the retaining wall seen in Figure 11. The colorized point cloud of the retaining wall helped identify defects and enabled advanced analytics of the data. This allowed Minnesota DOT to make data-informed decisions regarding the repair of the retaining wall.

Figure 11. Colorized 3D Point Cloud of MnDOT Retaining Wall Repair Project (Image courtesy of MnDOT)

Conclusion

UAS may prove to be a valuable tool for data collection for retaining wall inspections that helps eliminate risks associated with ground operations in areas that are steep, highly vegetated, or generally unsafe to navigate by foot. While UAS are still relatively new to retaining wall inspections, they have been identified as a resource for inspectors to access hard-to-reach areas, map large sites with ease, gather additional information, and find defects that could lead to a failure in the structure (Lovelace and Wells 2018).

References

Brutus, O., and G. Tauber. (2009). "Guide to Asset Management of Earth Retaining Structures." *Transportation Research* (Issue October).

DeMarco, M., Keough, D., and S. Lewis (2010). "Retaining Wall Inventory and Condition Assessment Program (WIP): National Parks Service Procedure Manual." *Central Federal Lands Highway Division.* Federal Highway Administration. Lakewood, Colorado. FHWA Publication Number FHWA-CFL/TD-10-003. (August). Pages 1–188.

Gerber, T., (2012). National Academies of Sciences, Engineering, and Medicine 2012. *Assessing the Long-Term Performance of Mechanically Stabilized Earth Walls*. Washington, DC: The National Academies Press. https://doi.org/10.17226/22721.

James, M.R., S. Robson, S. d'Oleire-Oltmanns, and U. Niethammer. (2017). "Optimising UAV Topographic Surveys Processed with Structure-From-Motion: Ground Control Quality, Quantity and Bundle Adjustment." *Geomorphology* 280, 51–66. https://doi.org/10.1016/J.GEOMORPH.2016.11.021

Lovelace, B., and J. Wells. (2018). *Improving the Quality of Bridge Inspections Using Unmanned Aircraft Systems (UAS)*. MnDOT Research Project Final Report 2018-26, http://mndot.gov/research/reports/2018/201826.pdf

Richards, J.A. (2013). Remote Sensing Digital Image Analysis: An Introduction, 9783642300622, 1–494. https://doi.org/10.1007/978-3-642-30062-2

Telleen, J., A. Sullivan, J. Yee, O. Wang, P. Gunawardane, I. Collins, and J. Davis. (2007). "Synthetic Shutter Speed Imaging." *Computer Graphics Forum* 26: 591–598. https://doi.org/10.1111/j.1467-8659.2007.01082.x

Online Resources

Federal Aviation Administration (FAA) Unmanned Aircraft Systems (UAS). https://www.faa.gov/uas/.

Federal Highway Administration (FHWA) Unmanned Aerial Systems (UAS). https://www.fhwa.dot.gov/uas/

Tech Brief

USE OF SMALL UNMANNED AIRCRAFT – BASIC FUNDAMENTALS

INTRODUCTION

State Departments of Transportation (DOTs) have found that the adoption of small Unmanned Aircraft Systems (UAS) as a supplemental tool across various use cases can increase safety, cost savings, and efficiency in collecting data. Given this interest, the Federal Highway Administration (FHWA) has been working with State DOTs to incorporate UAS into their operations. FHWA has assisted transportation agencies in understanding UAS applications, limitations, and use cases.

This document provides foundational information on UAS utilization including regulations, aircraft platforms, remote sensors, and UAS data management.

FAA REGULATIONS

UAS operators in both the public and private sectors must also adhere to statutory and regulatory requirements. Public aircraft operations (including UAS operations) are governed under the statutory requirements for public aircraft established in 49 U.S.C. § 40102 and § 40125. Additionally, both public and civil UAS operators may operate under the regulations promulgated by the Federal Aviation Administration (FAA). The provisions of 14 CFR Part 107 apply to most operations of UAS weighing less than 55 lbs. Operators of UAS weighing greater than 55 lbs may request exemptions to the airworthiness requirements of 14 CFR part 91 pursuant to 49 USC §44807. UAS operators should also be aware of the requirements of the airspace in which they wish to fly as well as the requirements for the remote identification of unmanned aircraft. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/.

Public aircraft operation is significantly limited in purpose under the statute and activities such as mapping, surveying, planning, or monitoring infrastructure construction and other generalized public works activities do not qualify for public aircraft authority. These small UAS activities must be carried out under the authority of 14 CFR Part 107 (Part 107). All government entities qualify for operation as a civil entity and may operate under the rules of Part 107. Unlike public aircraft operation, Part 107 has few restrictions on operational purpose. Operating in accordance with Part 107 requires the remote pilot in command to have a remote pilot certificate which is done on an individual pilot basis, while public aircraft operations require additional coordination with the FAA for approval for the organization, as well as determination that the function for which the operation would occur falls within the parameters of § 40125(a)(2). Public aircraft operations also require the organization to take on additional risk and liability. Table 1 provides a comparison of the requirements for Part 107 and public aircraft operations. As Part 107 has evolved, there are many advantages to flying under Part 107. It provides few restrictions on operational purpose, use of the Low Altitude Authorization and Notification Capability system (LAANC), fewer reporting requirements, and ongoing beneficial updates, which has made Part 107 a logical choice for many State DOTs.

Safety is a crucial element of each flight and is the responsibility of the Remote Pilot in Command (RPIC) (14 CFR § 107.19). The FAA regulations for the commercial use of small UAS help mitigate risk for operations. It is the duty of the RPIC to ensure that the small UAS is in a condition for safe operation (14 CFR § 107.15). Positive relationships with other agencies and the public to coordinate and notify those whom the operations may affect (e.g., medical helicopter flights operating in the vicinity, nearby airports, property owners) can help facilitate local awareness of recurring operations.

Table 1. Comparison of FAA Part 107 and Public Aircraft Operator

	Commercial Operations 14 CFR § 107	Public Aircraft Operator 49 U.S.C. § 40102 and § 40125
Aircraft Requirements	UAS <55 pounds	Self-certification by the public agency
Pilot Requirements	Part 107 remote pilot certificate with small UAS rating	Self-certification by the public agency
Airspace Requirements	Airspace waiver or authorization for Class B, C, D, E airspace.	Blanket Certificate of Authorization (COA) for Class G within the Continental United States or Jurisdictional COA for Specific Airspace in a specific operating area
Types of Operations	Visual Line of Sight, Class G Airspace, Below 400 ft above ground level (AGL)	Public Aircraft Operations (AC 00-1.1B)

Safety programs vary between agencies and involve an understanding of the nature of the work and the obstacles that are on-site within the operating area and airspace. It can be beneficial for State DOTs to develop risk management procedures that include the following topics:

- Part 107 Operating Rules - (14 CFR § 107.11-107.51)
- Airspace - (14 CFR § 107.41)
- Weather - (14 CFR § 107.49, 107.73, 107.74)
- Proximity to traffic and people - (14 CFR § 107 Subpart D)
- Radio interference - (14 CFR § 107.73)
- Emergency procedures - (14 CFR § 107.49, 107.73, 107.74)
- Identification and understanding of potential site hazards before flying - (14 CFR § 107.19, 107.49)
- Pilot experience and proficiency - (14 CFR § 107.65, 107.73)

RPIC of small UAS must be cognizant of the requirements of the airspace in which they wish to fly. When flying in controlled airspace, FAA uses the LAANC system to provide near-real time approval from Air Traffic Control (ATC). The above consideration for the development of risk management procedures is not comprehensive, States DOTs which are operating UAS should seek additional and substantive resources to assist with this process. The FAA offers extensive resources and information to help RPICs determine which laws, rules, and regulations apply to a particular small UAS operation. For more information, see https://www.faa.gov/uas/.

Types of UAS Aircraft

State DOTs may consider a variety of factors when investing in UAS to integrate across its operations. Two major types of UAS are available, based on the type of aircraft: multi-rotor and fixed-wing. There is an emerging third type of UAS that is a vertical take-off and landing aircraft that combines the utility of a traditional rotorcraft and a traditional fixed-wing. Each type is suited for different applications (see Table 2). Fixed-wing is the most advantageous when it is necessary to cover large areas efficiently. This is especially true if a waiver can be obtained for beyond visual line of sight operations. If large areas do not need to be covered, multi-rotor aircraft are typically preferred because they can take off and land vertically, maneuver under challenging environments, and hover in place. Multi-rotor aircraft are generally limited to 25-60 minutes of flight time. Depending on the site of interest and data collection mission goals, multiple batteries may be required. The hybrid fixed-wing UAS can take-off and land vertically and hover as a rotorcraft but can also transition into forward flight relying more on its wings to provide lift.

Table 2. UAS Aircraft Platforms Strengths and Weaknesses

Multi-Rotor UAS	
Strengths	**Weaknesses**
Vertical take-off and landing and flexibility on take-off and landing sites	Battery life
Hover in place	Generally lower payload capacity
Easy to fly	Lower endurance than fixed-wing
Maneuverable	More complex to maintain, due to more moving parts
Lower cost	Typically, higher noise level
Ability to change camera angles	
Precision maneuvering	
Fixed-Wing	
Long endurance	Cannot hover unless VTOL
Aerodynamically efficient	Higher vulnerability to turbulence
Cover large areas more efficiently	Need large take-off and landing zones
Vertical Take-off and Landing	
Long endurance	Not as versatile for complex maneuvers as rotorcraft
Vertical take-off and landing	Less efficient than multi-rotor while hovering, or while in take-off and landing configurations
Cover large areas efficiently due to airfoil/wing while in flight	Limited close range inspection capabilities
Aerodynamically efficient	Can be target for birds-of-prey
Reduced take-off and landing size zones than traditional fixed-wing	Higher maintenance costs

REMOTE-SENSING DATA

UAS aircraft can be equipped with different types of sensors for remote sensing, including high-resolution Red, Green, Blue (RGB) cameras, Light Detection and Ranging (LiDAR), hyperspectral, thermal/infrared cameras, and ultrasonic sensors. Selection of the UAS sensor depends on analysis and monitoring uses, the preference for images or LiDAR data depends on the project goals and budget, site characteristics, and accuracy or resolution requirements.

High-resolution RGB visual camera sensors come in a wide variety of configurations and specifications, which provide options when choosing a UAS for varying missions. Data collection using RGB cameras often benefits from basic photography knowledge, particularly given the rapidly changing lighting and weather conditions that can occur. Understanding the tradeoffs between ISO (the standard industry scale for measuring sensitivity of an image sensor to light), aperture (the size of opening; given by f-stop [as aperture increases, f-numbers decrease]), and shutter speed (controls how long the image sensor is exposed to light) is helpful for ensuring proper exposure and other aspects of image quality, such as noise and amount of motion blur. In turn, image quality may directly affect the accuracy of deformation estimates generated using photogrammetric techniques.

Structure from Motion (SfM) combined with Multi-view Stereo (MVS) is a photogrammetric range imaging technique for estimating 3D structures from two-dimensional image sequences to create multiple data outputs such as ortho-imagery, 3D meshes, Digital Elevation Models (DEMs), or point clouds. SfM software enables projects to be processed with or without geo-locations; however, accurate and well-distributed Ground Control Points (GCPs) may improve the global accuracy of the project.

LiDAR is an active remote-sensing technique where laser pulses are transmitted by the LiDAR system. These pulses travel down toward the earth's surface, reflect off a surface, and return to a sensor on the UAS platform where the roundtrip travel time and angle of the emitted pulse are measured. LiDAR scanners emit pulses of light (at speeds ranging from thousands to millions of points per second) to acquire X, Y, Z (3D) coordinates of points in an area of interest, producing a point cloud. Unlike photographs, because LiDAR is an active sensor, solar illumination (e.g., clouds, low sun angle) has minimal impact on the data quality. This may also help in highly vegetated areas. A LiDAR sensor for a UAS can be survey grade (5-10 millimeter accuracy) or mapping grade (1-3 centimeter accuracy), and as such, may be selected based on the magnitude of deformations anticipated and monitoring accuracy needed to meet data acquisition goals. Some UAS systems have bathymetric LiDAR capabilities, which may be important for mapping anything that is underwater.

Custom designed, small hyperspectral imaging systems are available for UAS. These systems are capable of imaging at multiple wavelengths within specific ranges such as Ultraviolet-Visible (UV-VIS) (UV-VIS; 250–500 nanometers [nm]), Visible and Near-Infrared (VNIR; 400–1000 nm), extended VNIR (600–1700 nm), Near-Infrared (NIR; 900–1700 nm), Short-wave Infrared (SWIR; 900–2500 nm), and Medium-wave Infrared (MWIR 3000–5000 nm). VNIR, extended VNIR, NIR, and SWIR tend to be the most common systems used in geologic applications such as mineralogy analysis and quantifying surficial moisture content. However, it is important to note that the imaging results could be sensitive to lighting conditions (i.e., the shadows and hot spots), which may introduce noise into the 3D point cloud.

Although UAS-SfM and UAS LiDAR techniques typically provide comparable data accuracies (with some differences, as a function of terrain and ground cover type), the application of UAS-SfM is generally less expensive, may impose less stringent requirements for the remote aircraft, may require less expert knowledge and training to operate, and could yield higher data densities. Therefore, SfM processing may be beneficial for small scale, less than 1.5 square miles, high-density topographic mapping applications based on its low cost, attainable accuracy, and usability. Nevertheless, moving objects, dense foliage and blurry imagery could be disadvantages if using SfM. UAS LiDAR may be an alternative when any of the following conditions apply:

- The area of interest (AOI) has homogeneous surface texture over a large area.
- Data acquisition through thick canopy is critical to characterize the terrain surface.
- Poor lighting conditions (e.g., extreme amounts of shadowing throughout the AOI, data collection at night) are anticipated.
- Surface characteristics derived from intensity returns are desired.
- Substantial vertical gradients exist throughout the AOI.
- Significant vertical (relative to flying height) obstructions are located throughout the AOI.

DATA MANAGEMENT

Utilizing UAS across operations could create large amounts of data. Collaborating with the agency's Information Technology (IT) department and developing a data management plan for UAS data may be helpful. The agency may also have policies and procedures related to data security, data sharing and storage that could apply to UAS data. Industry best practices for UAS data management are still being refined, but the following considerations may be helpful to State DOTs developing a UAS data governance plan:

- Where the UAS data will be stored, for example, cloud, network, or local server storage
- Access and permissions to manage the UAS data
- Whether all raw data be saved or only final deliverable data
- Data organization and shareability
- Life cycle of the UAS data

CONCLUSION

As State DOTs continue to discover ways in which UAS may be employed as a supplemental tool the agencies may find a variety of resources to be useful. Various publications, webinars, and other resources specific to State DOT use of UAS can be found at: https://www.fhwa.dot.gov/uas/. Several State DOTs have robust UAS programs and are willing to assist their peers. A basic understanding of UAS regulations, UAS platforms and remote sensors may be helpful in selecting equipment to meet data-collection goals of various use cases while also meeting overall goals related to increasing safety and efficiency.

ONLINE RESOURCES

Federal Highway Administration Unmanned Aircraft Systems Resources: https://www.fhwa.dot.gov/uas/

REGULATORY RESOURCES

Federal Aviation Administration Unmanned Aircraft Systems Resources: https://www.faa.gov/uas/

Tech Brief

USE OF SMALL UNMANNED AERIAL SYSTEMS FOR LAND SURVEYING

INTRODUCTION

Unmanned aerial systems (UAS) are being used to change the way data are collected for land surveying. By utilizing sensors that provide high-resolution images or light detection and ranging (LiDAR), or both, on small UAS, the systems enable the collection of highly accurate data with a high density of data points collected.

By utilizing photogrammetric and LiDAR point clouds, which are very dense sets of data that represent three-dimensional (3D) objects in space when collected via UAS in land surveying, more data can be collected in less time. The improved data collection capability can save costs while increasing productivity, not only by providing a better product, but also by preventing return visits to a site to collect additional data.

There are also several challenges to face in using small UAS for reliable surveys. System accuracy, weather, system limitations, regulatory restrictions, training, and liability are some that must be considered prior to using UAS.

Unmanned aircraft can fly lower than traditional aircraft and achieve the same if not better quality data at a lower cost for small to medium sized surveys. Much of the mapping can be completed using automated software to help ensure quality control with minimal training. UAS produce high-resolution imagery along with high-quality point cloud data that can be used in design to supplement conventional survey tools.

With the advent of UAS, many questions have been raised about what airframe, hardware, and software may be required to collect data that provide sufficient quality to be called “survey grade.” By utilizing ground control points (GCPs), real-time kinematic (RTK) positioning satellite navigation, or post-processed kinematic (PPK) global positioning, trained professionals can achieve survey-grade accuracy for deliverables using UAS.

While there are many facets to the questions, this tech brief provides basic knowledge on the best uses to achieve the desired results.

SURVEYING TOOLS

Surveying tools are evolving and allow for faster and denser data collection than ever before. Land surveying has undergone a lot of changes over the centuries, but perhaps not as rapidly as within the last 20 years (Reed 2015). Enhancements to the state of the art, such as global positioning systems (GPS), LiDAR, robotic total stations, and now UAS, allow for surveying at scales that weren’t possible with traditional technologies of the past.

What once took a large, full-staffed survey crew months, even years, to survey can be completed within days using the advanced technologies of today, and with a 1–2 person crew. Surveyors can also achieve higher accuracy and precision without needing to remove vegetation due to line-of-sight restrictions.

During the past 50 years, surveying and engineering measurement technology has made five quantum leaps: electronic distance meter, total station, GPS, robotic total station, and laser scanner. UAS or drones (also known as unmanned aerial vehicles or UAVs) are becoming the sixth quantum leap in technology (Willis 2013). What Willis envisioned in 2013 has now become a reality and is changing the way many survey firms collect data.

Safety is another important aspect when discussing UAS. Traditional surveying methods were often very dangerous, being exposed to traffic, dangerous terrain, obstacles, and unexpected situations. UAS can be used to collect data where it is dangerous or extremely difficult for a person to access, such as active roadways, riverbeds, unstable landslide areas, steep terrain, toxic areas, and cliffs.

By utilizing UAS, we are able to collect high-quality survey data and minimize the time surveyors spend in dangerous situations. The Moki Dugway, Utah landslide was an instance where photogrammetry was used, and it would have been impossible to safely survey the area with traditional methods (see Figure 1).

UDOT

Figure 1. Moki Dugway, Utah landslide 3D point cloud collected using UAS photogrammetry

ROTORCRAFT VERSUS FIXED-WING UAS

Many choices exist when it comes to the procurement of a UAS fleet. Most fall within two main classes: rotorcraft and fixed-wing (see Figure 2).

Pixabay (left), Wingra (right), used with permission

Figure 2. Rotorcraft (left) and fixed-wing (right) drones

It is beneficial to understand the benefits and weaknesses of each class of aircraft. Each platform has its strengths and weaknesses, and it is important to understand the characteristics of each to ensure they will meet the needs of your agency.

Both rotorcraft and fixed-wing UAS may be needed to complete an operation at times. The primary goal should be to base the decision on the sensor and the compatibility of the aircraft to the software being used for flight and processing. Tables 1 and 2 list the strengths and weaknesses of rotorcraft versus fixed-wing UAS.

Rotorcraft are useful in many situations and are typically less expensive than fixed-wing aircraft; however, fixed-wing aircraft are more efficient for flight. Fixed-wing UAS depend on their wings for lift and the motor to move the aircraft, while rotary-wing aircraft must depend on their energy to keep them airborne at all times.

Rotorcraft are excellent for capturing data in difficult areas such as those during bridge inspections and in urban areas where space is limited. They are also much more versatile than fixed-wing aircraft.

Due to the efficiency of fixed-wing UAS, they have longer flight times, which are typically double that of a rotorcraft UAS. This makes them an efficient tool for mapping large areas. The weakness of fixed-wing UAS comes from their lack of being able to stop in mid-air and the need for a larger area in which to take-off and land. Rotorcraft are easier to use when in areas where there are many obstacles present or if limited space is available for take-off and landing operations, such as an urban environment.

Table 1. Rotorcraft UAS strengths and weaknesses

Strengths	Weaknesses
Vertical take-off and landing and flexibility on take-off and landing sites	Battery life
Stability	Aerodynamics/less efficient
Easy to fly	More maintenance
Variety of aircraft/sensors easily available	Expensive repairs
Ability to hover	Slower airspeed
Ability to change camera angles	Smaller payload capacity
Precision maneuvering	

Table 2. Fixed-wing UAS strengths and weaknesses

Strengths	Weaknesses
More aerodynamic/efficient	Larger area ftake off and landings
Fewer parts to maintain	Difficult to fly manually
Glide ratio	Higher speeds
Longer flight times/endurance	Inability to fly slow or hover while taking images
Large area coverage	Fixed camera angle on most aircraft
Higher speeds	Target for birds of prey

GPS EQUIPMENT

The accuracy of the data can be attributed to not only the sensor being used but also the quality of the GPS on board the aircraft. The GPS solutions available on UAS fall into three categories: consumer, RTK, and PPK. Most lower-cost aircraft have consumer-grade GPS integrated with the aircraft. This can be problematic if additional steps aren't taken to increase the accuracy of the data captured. Typically, if higher accuracy is needed, GCPs, which are addressed more below, are necessary. As more UAS have been utilized, higher quality GPS solutions have been made available.

As mentioned previously, two other solutions that can reduce the number of GCPs, while still maintaining quality, are RTK and PPK solutions. These help enhance the precision of the satellite positional data, which leads to greater accuracy and precision of the data collected. If utilizing aircraft with RTK or PPK solutions, it can reduce the number of required GCPs, but not eliminate them completely.

The Utah Department of Transportation (UDOT) has found that including GCPs is necessary for accurate data regardless of the technology used. In addition to the RTK and PPK solutions on the aircraft, a base station is also required, which adds additional cost. Most survey companies already have base stations as part of their equipment or utilize a statewide continuously operating reference station (CORS) or virtual reference station (VRS) network. It is beneficial to confirm that the system on the aircraft is compatible with the base station that is being used. Even with these solutions, considerations must be taken to understand the limitations.

RTK positioning satellite navigation can record accurate corrections, yet it can have issues if the signal is lost during flight. If the signal is lost, the positional data is unknown and will not capture or record the corrected positions to the metadata while the image is being captured. This can cause an image to be rendered useless.

PPK global positioning can provide more flexibility, as it doesn't require constant communication with the base station during flight. This prevents signal loss from interference or obstruction during flight, which can occur when using RTK solutions. The data can then be processed and input into the system after the flight to geotag the images with the proper correction data. PPK solutions also allow data to be collected from more than one source for redundancy during flight.

While these are viable solutions for most projects, there are GPS limitations. Positioning accuracies for GPS measurement and mapping using PPP or RTK can be very challenging even under the best conditions. Global Navigation Satellite System (GNSS) signals can be affected by space weather in the ionosphere causing signals to be slowed. Additionally, accuracy may be compromised by other factors such as satellite shadowing, non-line-of sight receptions, signal diffraction, or multipath effects. These are real world challenges regarding the use of GPS that have also faced the safety-critical aviation industry. Checking the quality of the data is important and should be incorporated into the workflow to fully verify the accuracy of what is being collected.

GROUND CONTROL POINTS

GCPs can be any seen feature on the ground that can be identified in the aerial imagery. Typically, aerial targets are used, whether by painting, tape, or temporary targets (see Figure 3).

UDOT/Meridian Engineering, Inc.

Figure 3. Aerial target for GCP

The points are precisely measured for x, y, and z values and assist with improving the quality of the aerial data.

One of the most critical factors in ensuring a profitable and accurate drone survey is ground control (Campbell and Katz 2018). Without the use of GCPs, issues can arise that aren't always apparent, such as warping or scaling of the imagery and the point cloud. It is important that the points are visible and placed properly to prevent errors in the data. Having the points not disbursed properly can cause issues worse than not using them at all.

GCP Placement

It is important to place the GCP locations disbursed around the site in a manner that resembles that of the five side of a die, as shown on a sample site in Figure 4.

UDOT

Figure 4. Placement of GCPs on the five side of a die (one die next to the other in the aerial image on the right)

The points should be uniformly placed around the site as shown. If the points are too close to the edges of the site, warping can occur. For longer corridors, the control points should be staggered along the roadway. Other technical considerations are as follows:

- Keep GCPs no more than 500–1,000 ft apart from each other
- Distribute points throughout the flight area
- Prevent the location of the points being located on the far edges of the flight area where overlap is not sufficient
- Have targets large enough to see for the specified ground sampling distance (GSD)
- Avoid obstructions and shadow areas

GCP Visibility

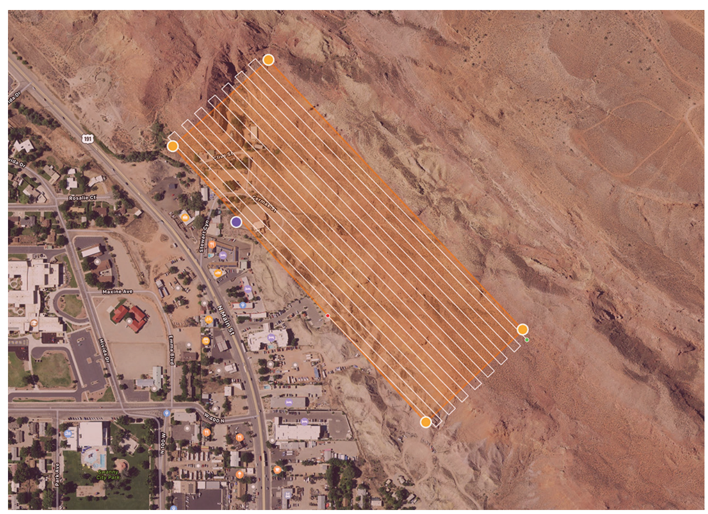
When placing GCPs, the visibility of the target from the air is just as important as the disbursement around the site, and it isn't always apparent from the ground if the target can be seen from the sky. It is important to assess the area for any obstructions that could obscure the point during different times of the day and make it difficult to see and select the target when processing the data (see Figure 5).

UDOT

Figure 5. Examples of problematic GCP locations: guardrail shadow (top), paint on dirt that can wash or blow away (center), and blurry numbers (bottom)

Figure 5 (top) illustrates the shadow from a guardrail that obscures the GCP, making it difficult to see and select the target when processing the data. The type of material (e.g., sand, loose soil, silt) on which the GCP is placed or painted can also have an impact on the longevity of the target, and Figure 5 (center) shows a target that is painted on the dirt. The target may only be visible for a short time until the wind or rain blows or washes the paint away. Using aerial tape or temporary targets is often preferred when placing targets on natural ground. It is also important to have good contrast on the targets for the best visibility.

GCPs also should be placed in areas where they have low probability of a vehicle parking on top of them and obscuring the view from the air. It is also important to consider the size of the numbers and ensure they are large enough to be identified from the air. If the numbers aren't large enough, they will become blurry and it may be difficult to determine one point from another, as shown in Figure 5 (bottom).



Paul Wheeler

Figure 6. Example of land survey flight plan

FLIGHT PLANNING

Flight planning is crucial to a successful mission (see Figure 6). Many considerations must be planned to ensure quality data and a safe flight. It is advisable to plan a site visit prior to flying to scan for any potential obstacles or conflicts prior to flight. Brief descriptions of various planning considerations follow.

Time of day (e.g., lighting conditions): Lighting and shadows can play a large part in achieving optimal results, especially when mapping large sites. Areas that are either overexposed or in shadow make it very difficult for the processing software to match similar features, which will leave areas of the data blank.

Another consideration when surveying areas during multi-day missions, if one flight is completed in the morning and another in the evening, for example, software can have issues matching key points in those areas and see them as two different surfaces, causing errors in the data. A way to negate this effect is to fly when the lighting is similar for the flight lines, or process the areas separately.

Airspace and air traffic (e.g., low flying planes or helicopters, nearby airport): When surveying in controlled airspace, it may take extra time to receive authorization to fly. An alternative plan is also useful in case the authorization request is rejected.

When flying near a heliport or airport, it may prove difficult or impossible to safely fly without impacting the other air traffic. An aviation band radio or automatic dependent surveillance-broadcast (ADS-B) in device to monitor traffic in these areas may mitigate any safety issues.

Obstructions (e.g., powerlines, trees, structures): Distances can be deceiving from the ground. Before completing an autonomous mapping mission, it is important to determine the actual height of obstacles above the ground to prevent incidents.

Weather and temperature: Due to limitations in sensors, hardware, and the regulatory environment, weather may impact the ability to fly. Temperature has a drastic effect on the performance of the aircraft and its batteries. Performance may differ due to heat, cooling, and density altitude.

Suitable take-off and landing sites: For a suitable take-off and landing site, a portable, durable landing pad that can be placed on the ground is useful. Areas with fine dust or dirt can cause the camera lens to become dirty on take-off and landing, in addition to getting particulates into the engine, which can cause damage and reduce the life of the motor.

When planning a flight, one or more backup or alternative landing sites are important in case the primary site becomes unusable.

Terrain: Terrain can have a drastic effect on the overlap settings for the images. If the software doesn't follow the terrain and provide a relative constant altitude, it can change the GSD and reduce the accuracy. Depending on how drastic the changes are in altitude, it may make it impossible to use certain images. By using software that will follow the terrain, it will keep the GSD constant and make for improved data sets.

Overlap settings: Overlap is an important part of the settings in the software that can have a drastic effect on the quality of the data gathered. An understanding of the proper overlap to achieve the desired results for both front and side lap is needed. If the mapping area includes simple objects, enough images to obtain four angle measurements are necessary, while complex objects require nine angle measurements (see Table 3).

Table 3. Image overlap setting recommendations

Overlap Characteristic	Front Angle	Side Angle
Minimum	75%	60%
Dense vegetation	85%	70%
3D models (i.e., towers, buildings)	90%	60% at different height levels

Landscape characteristics to consider in the flight plan include trees, fields, corridors, and mountains. Areas with dense vegetation may need 90% overlap to achieve the desired accuracy; however, it is not advisable to use a higher overlap than needed, as it can have an exponential effect on flight and processing time.

Camera settings: To obtain the highest quality images, it may be necessary to adjust the settings manually for the camera to properly set the white balance, aperture, and shutter speed.

Battery charging capabilities: Unless mapping smaller sites (when minimal battery life is needed), it is beneficial to have the capability to charge batteries on site. Two options include power inverters that run off 12 volts on a vehicle or a portable energy source that has enough capacity to charge the batteries as needed for the project.

Mapping software: To work effectively, the mapping software should have, at a minimum, the ability to adjust camera settings, resume at the last point when changing batteries, and include terrain following, GSD indication, and overlap setting features.

Permits or authorizations: Authorizations including permits are required to fly in a controlled airspace and may be required in locations such as national parks. Prior notifications to entities like national parks can also help foster good ongoing relationships.

Use of Mapping Software

The majority of the mapping software available is programmed for autonomous missions in order to ensure the proper overlap and flight lines and limit pilot error. While this can allow for ease-of-use in the field, it is necessary to understand what the software is doing and why. It is important to understand all the nuances of the software to reduce the possibility of a crash or unsatisfactory mapping results.

For example, if the return-to-home altitude is set below the height of the tallest obstacle, the UAS may fly directly into the obstacle. It is important to check all of the settings for the aircraft and software prior to each flight to help prevent otherwise easily avoidable problems during flight and data collection.

Many different varieties of mapping software are available that can achieve different goals. The following questions/features merit evaluation prior to purchasing the software: Does the software offer terrain following? Does it have the ability to resume a mission after changing a battery? Can the camera angle be adjusted?

Figure 7 depicts the capability of mapping software to follow the terrain to fly a constant altitude above the ground with changing terrain elevation.

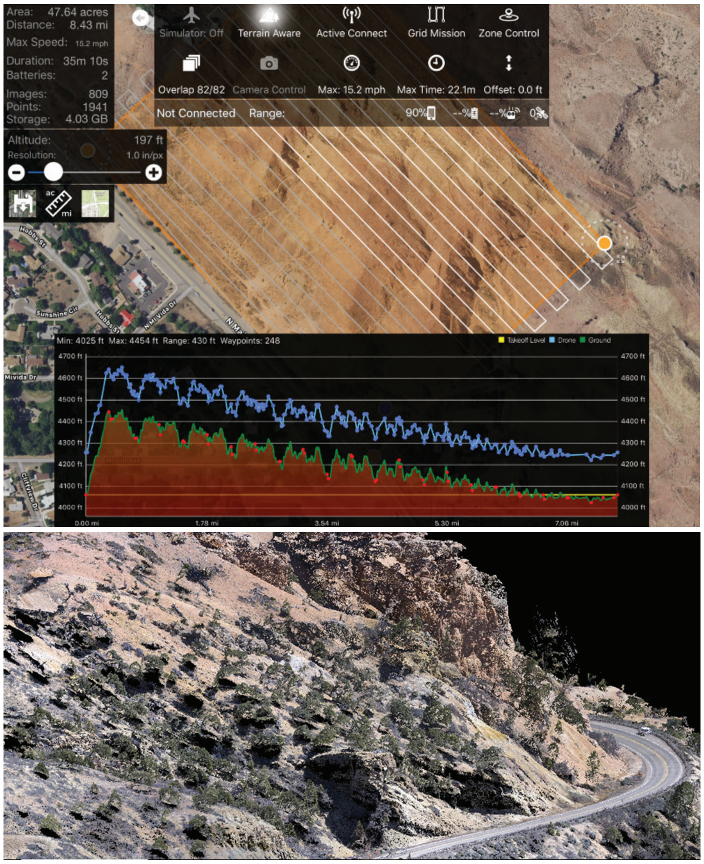


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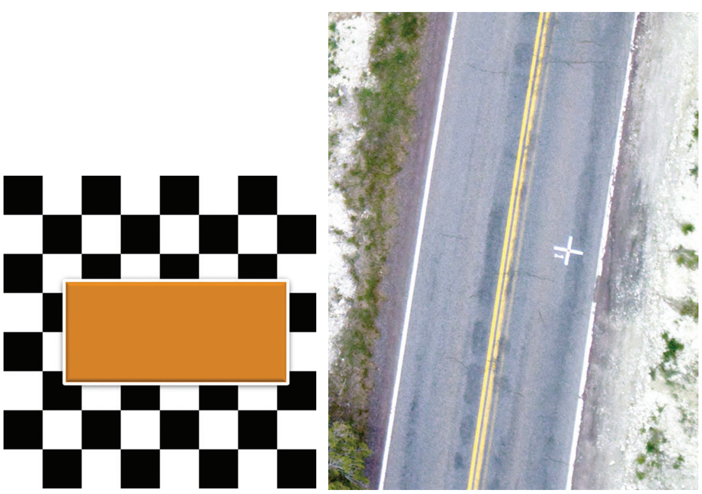
Figure 7. Terrain awareness feature in mapping software

Ground Sampling Distance

Understanding GSD is important to achieve the desired results and can be overlooked. By understanding the concept, it can save time by gathering the data for the context in which it is needed. Figure 8 demonstrates an example of GSD in the context of capturing the proper ground sampling distance.



Paul Wheeler (left), UDOT (right)

Figure 8. GSD example

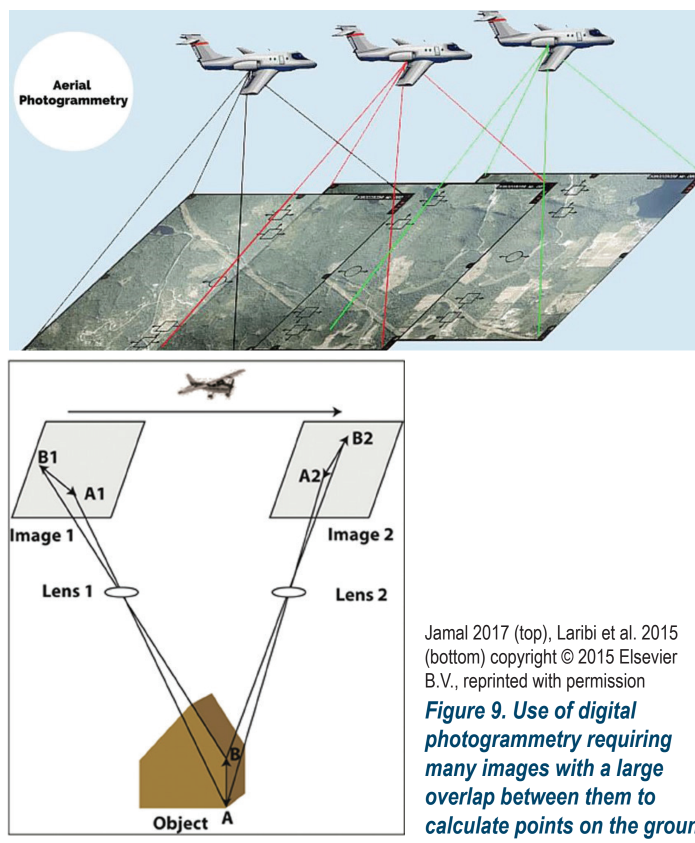
Each square in the checkered image represents a pixel on the image. To measure a paint line that is 4 in. wide, for example, a GSD that is less than that (or of what is being measured) is necessary. For a 4 in. painted line, a GSD less than 4 in. per pixel is necessary for the accuracy to define the line. However, too low of a GSD increases both the flight and processing time exponentially.

PHOTOGRAMMETRY POINT CLOUD VERSUS LIDAR POINT CLOUD

Each point in a point cloud is defined with an x, y, and z coordinate. Additional information, such as intensity values, red-green-blue (RGB) color information, or classification, can also be stored within the data set. Point clouds can be created from images or LiDAR. Both collection methods have their advantages, yet also some disadvantages. Photogrammetry point clouds can be produced for less cost than a traditional LiDAR point cloud.

Advances in technology have created the ability to take overlapping images and develop them into a dense point cloud whether the source is from a cell phone or from a UAS. This allows for a lower-cost solution to create rich data that are also infused with RGB color, so that it looks similar to an image that has coordinate values attached to each pixel for x, y, and z.

Photogrammetric point clouds use many images with a large overlap between them to calculate points on the ground, as illustrated in Figure 9.



Jamal 2017 (top), Laribi et al. 2015 (bottom) copyright © 2015 Elsevier B.V., reprinted with permission

Figure 9. Use of digital photogrammetry requiring many images with a large overlap between them to calculate points on the ground

For a majority of situations, photogrammetry point clouds are less expensive and oftentimes produce a more dense point cloud. However, the weakness of photogrammetry lies in the penetrating properties of LiDAR, which can penetrate through vegetation, with multiple returns. LiDAR also achieves better accuracy on flat surfaces, such as pavement, where photogrammetry point clouds tend to have a lot of noise that is inherent for these surfaces.

Another item to consider is the quality of the LiDAR unit. Less-expensive units without calibrated lasers can be less accurate than photogrammetry point clouds with GCPs.

For softscape (vegetated) surfaces with low vegetation, UAS aerial photogrammetry can achieve 0.1 ft accuracy or better with confidence if using GCPs, RTK positioning satellite navigation, PPK global positioning, or a combination of the technologies. LiDAR creates a similar point cloud but is collected differently.

While photogrammetry requires the image to be clear and have the same points visible in multiple images, LiDAR can be used in environments that are shadowed, or even at night. LiDAR sends out light beams that can penetrate through vegetation by using multiple returns while photogrammetric point clouds cannot.

The biggest disparity between the two is the cost. LiDAR is much more expensive to procure and maintain and isn't always needed. LiDAR may be the best solution for 3D quantities on pavement sections, when areas have a lot of shadows, for fine edge detection, and for vegetated areas. LiDAR also requires less processing, which can increase productivity over processing large photogrammetric data sets. Using specialized software to process LiDAR images can also help utilize its strengths given the large data size. It is also beneficial to have a computer that is capable of loading and processing the point cloud data efficiently.

The benefit of using UAS for either sensor is the ability to capture the data from an aerial perspective, which creates highly detailed imagery and data that are able to give a new perspective that wasn't always readily available otherwise. The cost saved from one project may justify the cost of procuring a UAS.

Point clouds have a distinct technical advantage over traditional breakline surveying methods. Breakline surveys only capture the data where it's collected at each point and often fail to define the specific nuances of a surface. Point clouds are the most comprehensive method of modeling the terrain, and, as such, contours should have no place in today's digital mapping environment and are unnecessary and should not be used to define a topographic surface in digital form (Abdullah 2017).

Figure 10 illustrates the difference between a traditional breakline survey and a point cloud.

UDOT

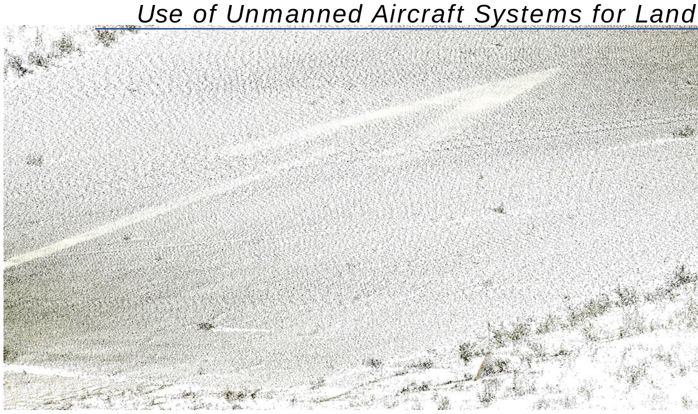
Figure 10. Breakline survey (top) versus point cloud (bottom)

A breakline survey only captures the top and bottom of the slope as shown with the red lines. By only capturing these two areas, the middle section and all the deviations and fine details are not included in the data. A point cloud captures all this detail and more to create a more accurate representation of the surface.

Figures 11 and 12 illustrate the difference between point clouds generated using photogrammetry versus LiDAR.

UDOT/W. W. Clyde & Co.

Figure 11. Photogrammetric point cloud



UDOT

Figure 12. LiDAR point cloud

The photogrammetric point cloud gives the appearance that the pavement is rutted and wavy due to the noise inherent in the data. Using photogrammetry on asphalt, the software has difficulty deciphering the pavement nuances due to the similarity between the images. The LiDAR, on the other hand, shows the true nature of the surface and shows the vegetation that is growing out of the pavement.

For pavement surfaces, LiDAR produces a technically superior result due to the differences in the way the point cloud is produced and processed. LiDAR reflects directly off the surface, giving a true representation of the surface.

This example clearly shows the benefits that LiDAR has over photogrammetric point clouds on surfaces that are similar in nature, such as asphalt or concrete.

Photogrammetric Camera Angle

The camera angle can have a significant impact on the quality of the data. If the terrain is flat, nadir (directly downward from the observer) works the best; but, if there are deviations, outcroppings, or cliffs, this camera angle can leave holes or shadows in the surface data. For most mapping, nadir works best; however, a different camera angle may be the optimal solution to sufficiently capture vertical faces when mapping steep terrain with cliffs or outcroppings.

Figure 13 illustrates data collected with a nadir camera angle in Mexican Hat, Utah, which has high cliffs and steep terrain.

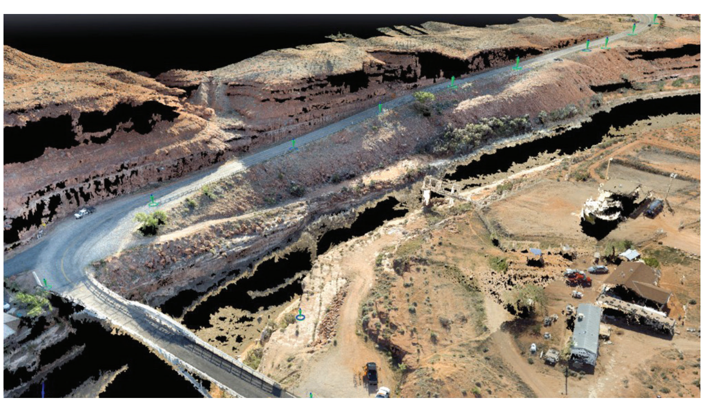


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Figure 13. Nadir camera angle in Mexican Hat, Utah

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Figure 14. 70-degree camera angle in Mexican Hat, Utah

The black areas show gaps or holes in the data on the cliff faces where the camera wasn't able to capture data on the cliffs. Contrast that with Figure 14, which was collected using a camera angle of 70 degrees.

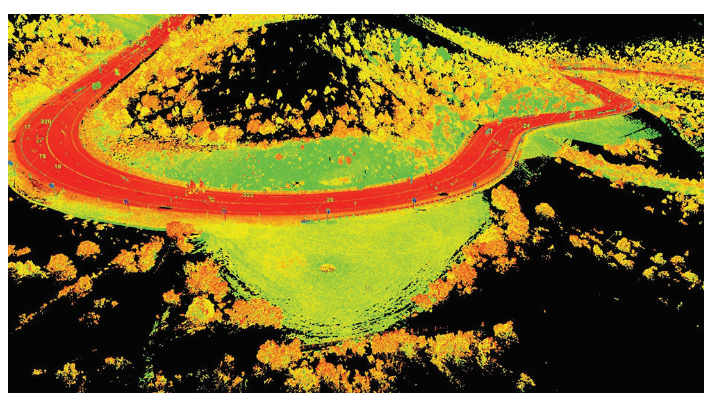
By using a 70-degree angle, the data on the majority of the terrain was able to be sufficiently collected using UAS.

Proper planning and using the proper camera angle and sensor for the terrain can prevent return trips to capture missed areas in the data. The key is to properly plan for the terrain being flown and use the proper camera angle for each situation.

HYBRID METHODS

Different tools and sensors have inherent strengths and weaknesses. By using the strengths of each tool and combining the data to create a hybrid model, surveyors can assimilate the best possible data set. Where photogrammetry is weak on pavement, for example, LiDAR is well suited to collecting data on pavement.

As an example, the Utah Department of Transportation (UDOT) utilized this hybrid method on the State Road 20 (SR-20) project. The roadway data and images were collected using terrestrial LiDAR, while the softscapes were collected using photogrammetric point clouds. The two were combined into a hybrid model. By combining the use of these technologies, it allows for a dense, highly accurate, 3D model that has all the strengths with minimal weaknesses (see Figure 15).



UDOT/ W. W. Clyde & Co.

Figure 15. Hybrid model SR-20 project

The aerial imagery from the UAS was also used to colorize the LiDAR to save time and eliminated the need for the terrestrial scanner to take images, which can be time consuming. The data were used to verify construction progress and quantities with the 3D model from design. By utilizing this and other technologies, a significant savings of $82,672 (2.58%) was realized on this project.

QUALITY CONTROL/QUALITY ASSURANCE

To verify the accuracy and precision of the data, it is worthwhile to check the data on the ground and not always depend on the verification reports provided by the software. By taking random survey points throughout the area and using it to compare with the point cloud, it allows for quality control and quality assurance to determine the actual accuracy of the data.

Some software packages allow for using checkpoints, but not all. The verification reports are required on all hardscape and softscape surfaces for UDOT projects. This helps to provide confidence and knowledge of the accuracy and precision of the data collected.

FAA REQUIREMENTS

UAS operators in both the public and private sectors must adhere to statutory and regulatory requirements. Public aircraft operations (including UAS operations) are governed under the statutory requirements for public aircraft established in 49 USC § 40102 and § 40125. Additionally, both public and civil UAS operators may operate under the regulations promulgated by the Federal Aviation Administration (FAA).

The provisions of 14 CFR Part 107 apply to most operations of UAS weighing less than 55 lbs. Operators of UAS weighing greater than 55 lbs may request exemptions to the airworthiness requirements of 14 CFR Part 91 pursuant to 49 USC § 44807.

UAS operators should also be aware of the requirements of the airspace in which they wish to fly. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/.

CONCLUSIONS

UDOT has found UAS to be a great asset. What started as a test in 2011 has grown to a fleet of more than 40 UAS in 2019. UDOT's uses for UAS grows each day due to the ease in which they allow for safe and accurate collection of data. UDOT has found the key to quality survey data using UAS is to use the proper tools for the job.

UAS provide advantages but don't necessarily fully replace the other survey tools being used. The hybrid model or method achieves the greatest results by using all tools that are available and combining them together. Determinations on the proper aircraft, sensor, and pre-flight planning are vital to achieving satisfactory results.

UAS have increased in popularity among the land surveying community due to the repeatable accuracy that can be attained from using these new tools. The sole use of UAS may not always give the desired results, so it is important to understand the weaknesses and supplement the data with use of other technologies when needed. This is why UDOT has adopted the hybrid method to ensure the accuracy and precision needed.

By sharing lessons learned through utilization of these tools, it can increase agency productivity, help agencies collect more accurate data, and foster the next generation of land surveyors into the field.

REFERENCES

Abdullah, Q. A. 2017. Mapping Matters: Breaklines for Lidar Data, Do We Really Need Them? *Photogrammetric Engineering and Remote Sensing*, Vol. 83, No. 9, pp. 599–602. https://www.asprs.org/wp-content/uploads/2018/03/09-17-MM.pdf.

Campbell, L. and D. Katz. 2018. How to Use Ground Control in Drone Surveying. *Point of Beginning (POB) Magazine*. https://www.pobonline.com/articles/101529-how-to-use-ground-control-in-drone-surveying.

Jamal, H. 2017. Surveying and Leveling: Principal Method of Terrestrial Photogrammetry. About Civil Engineering. https://www.aboutcivil.org/Principal-method-of-Terrestrial-Photogrammetry.html.

Laribi, A., J. Walstra, Jan, M. Ougrine, A. Seridi, and N. Dechemi. 2015. Use of Digital Photogrammetry for the Study of Unstable Slopes in Urban Areas: Case Study of the El Biar Landslide, Algiers. *Engineering Geology*. Vol. 187, No. 17, pp. 73–83. https://www.sciencedirect.com/science/article/abs/pii/S0013795214003524?via%3Dihub.

Reed, J. 2015. Land Surveying Transforms Along with Technology. *The Gazette*. https://www.thegazette.com/subject/news/business/land-surveying-transforms-along-with-technology-20150307.

Willis, F. 2013. How Can Drones Transform Surveying? *Point of Beginning (POB) Magazine*. https://www.pobonline.com/articles/96996-how-can-drones-transform-surveying.

Tech Brief

USE OF SMALL UNMANNED AERIAL SYSTEMS FOR CONSTRUCTION INSPECTION

INTRODUCTION

Unmanned aerial systems (UAS) have become increasingly popular on construction sites. In fact, UAS utilization has flourished in nearly all areas of engineering and construction. At the same time, both the affordability and capabilities of small UAS have dramatically increased.

Many transportation agencies and contractors have begun to implement UAS efforts into their daily work flow. This has been especially effective in transportation infrastructure construction inspection. These users have been able to reduce inspection times, improve inspection effectiveness, increase safety, and lower the cost of inspection with a modest investment in training and equipment.

Currently, UAS are being used by agencies for a variety of inspection tasks including erosion control, quality assurance and quality control (QA/QC), structure inspection, and construction progress monitoring. In these cases, the UAS has become an integrated part of the inspectors' tool kit.

The purpose of this document is to provide information about successful UAS integration into infrastructure construction inspection practices.

FAA REQUIREMENTS

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INSPECTOR PILOTS VERSUS PILOT INSPECTORS

As with many new and emerging technologies, our workforce needs to be brought up to speed with training and hands-on demonstration. The implementation of a UAS, wrapped in a whirlwind of tech and aviation acronyms, can seem like a daunting task. Often the temptation arises to outsource UAS inspections to UAS or drone companies that offer turnkey services. However, it is important to understand that being licensed to operate a UAS does not qualify the operator as an inspector.

If the decision is made to outsource work to UAS or drone companies, agency staff should consider insurance requirements. The owner's insurance requirements will require the UAS operator to provide insurance, as well as name all parties as insured.

Experienced inspectors are essential in the decision-making process of selecting areas of interest for inspection and understanding the level of detail required at each location. The visual feedback of the UAS allows each inspector to decide and act accordingly, adjusting the inspection in real time (Zainudin 2015). Accordingly, the presence of a knowledgeable inspector during flights is critical for optimum efficiency and quality.

UAS FOR CONSTRUCTION INSPECTION

When considering the acquisition of a UAS for construction inspection, a variety of factors should be weighed.

In UAS construction inspection, rotary wing aircraft generally play the primary role. These aircraft typically consist of quad- and hex-copter configurations.

At this time, there are more than 100 available UAS sensors on the market. However, many of these sensors are emerging technologies and have not found their way into everyday use. This document focuses primarily on sensors in the visual and infrared spectrums.

Visual camera sensors are available in a wide variety of configurations and specifications. Primary cameras are generally mounted on the front of the aircraft often on a two- or three-axis stabilized gimbal.

When considering UAS for inspection use, there are a number of platform features to consider:

- Sensor size
- Focal length
- Camera combinations
- Obstacle avoidance sensors
- Battery life
- Payload

Given that each inspection is different, no exact configuration is recommended for each payload type. However, some trends are noted across inspection UAS users. Table 1 shows the primary factors for each inspection type.

Table 1. UAS key considerations

Factor	Sensor Size	Obstacle Avoidance	Wide Angle Lens	Adjustable Focal Length	Battery Life	Top Mounted Camera	Thermal Camera
Erosion Control							
Construction Progress							
Construction QA/QC							
Structures							

FHWA

While each agency's needs will vary, there are some general guidelines for each factor. When considering sensor size, most entry level UAS pilots will gravitate toward comparing sensor resolution by pixel count, even though the size and inherent complexity of the sensor are often more important than the pixel count in most cases. Larger sensors generally have a better dynamic range (DR) and much lower signal to noise ratio (SNR). Increased DR allows better clarity in unevenly lit subjects and a lower SNR results in less image "static."

Quick Tip: If the work involves detailed and complex subjects, consider a UAS with a 1-inch image sensor.

Obstacle avoidance sensors are becoming standard equipment on many commercially available UAS. For operations near objects, or where the PIC may have difficulty gauging range, it is recommended to have, at a minimum, forward-facing obstacle avoidance sensors. Depending on the application, additional sensors may be useful.

When considering the lens for visual or infrared cameras, first consider the task at hand. Wide-angle lenses provide context, allow for easier first-person control, and allow quick inspection of large areas. Wide-angle lenses are the most common and generally have a field of view of 70° or greater. Some UAS cameras have the ability to provide optical zoom for detailed examination of objects without the need to have the UAS close to the subject. For these types of inspection, a minimum of 2X optical zoom should be considered.

Work that involves overhead inspection requires the ability to mount the camera on top of the UAS. An alternative may be a camera that allows upward vertical tilt.

A variety of infrared (IR) cameras are currently available for UAS platforms. Due to their cost, however, they have been slow to be implemented into general construction inspection. Lower-end IR cameras often do not provide enough detail for construction inspection while a mid-range IR camera can easily double the cost of a UAS. In some applications, the IR camera replaces the visual spectrum camera making first-person control more difficult. Many inspectors become familiar with UAS inspections before acquiring an IR camera.

Quick Tip: Consider an IR sensor with a sensor size of more than 240x320 pixels or dual cameras with the ability to blend images for greater clarity during inspections.

Construction inspection UAS primarily consist of rotary wing aircraft. These UAS are generally limited to 20–25 minutes of flight time, although some can approach closer to 30 minutes. For inspection tasks that require long hover times or the inspection of large areas, extra battery life may significantly reduce downtime.

Quick Tip: Spare batteries and the ability to charge batteries from a vehicle can make or break an inspection trip.

UAS vary in price nearly as much as they do by configuration. Typical entry-level commerical platforms start around $1,000 while professional models can easily climb above $50,000. For a state agency perspective, inspectors operating on North Carolina DOT (NCDOT) projects, for example, generally have platforms in the $2,000–$5,000 category.

SAFETY

The safety program requires an understanding of the nature of the work and the limitations and/or obstacles that are onsite. For example, if one or more cranes or concrete boom pumps are present, the UAS pilot needs to understand where to avoid flying. Also, the work crews on the ground need to understand the fight plan and be in contact with the pilot to prevent the crew from being surprised by UAS presence.

It is important for the UAS pilot and the project supervisor to develop a job hazard analysis (JHA) that lists all of the potential site hazards prior to flying. Other concerns may include the specified flying time period and zone constraints based on type of construction and density of construction personnel.

A best practice is to have a visual observer who has active radio contact with local air traffic and the PIC at all times and can alert the PIC of any conflicts with manned aircraft or fixed objects.

OUTPUTS AND DATA PROCESSING

Most commercially available UAS are capable of recording and displaying images and videos using both visible and infrared sensors (if equipped). The preference of using video or images to complete an inspection varies between inspection type, operators, and even sites.

Images provide an instantaneous snapshot at a particular time, offering concise documentation that can be scaled and measured. Videos provide an immersive record that depicts an evolution of perspective. Image inspections can create hundreds of files for a single inspection that need to be sorted and organized. Video inspections generate large data files that can quickly fill up storage space on computers and servers.

Proficiency using image editing software can be an essential part of UAS post-processing because the ability to digitally filter and enhance different aspects of inspection images can be invaluable in discerning details and communicating inspection issues (see Figure 1).

The market has evolved to provide a wide range of post processing software and services and various price points and payment options, from onetime fees to recurring licensing, and capabilities ranging from simple volumetric calculations to complex three-dimensional (3D) point clouds.

Images from Paul Rogers

Figure 1. Simulated image editing software screenshot

Photogrammetry software that helps extract geometric information from two-dimensional (2D) images or video is another valuable tool for the construction inspector. Primarily targeted toward survey applications, these software packages allow for the generation of geo-referenced orthomosaics (see Figure 2).

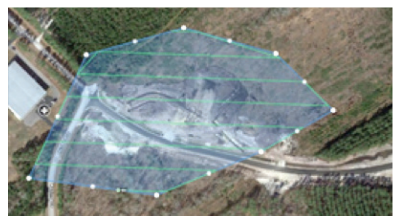


Image from Paul Rogers

Figure 2. Image editing and orthographic software screenshot

Unlike uncorrected aerial images, orthomosaic images can be used to measure true distances with accurate representations of the earth's surface adjusted for topographic relief, lens distortion, and camera tilt. A variety of companies offer standalone platforms and subscription-based services. The ability to share files and data between offices or between contractors and consultants can be an important consideration.

UAS INSPECTIONS

UAS are being used for a variety of construction inspection roles, the majority of which are carried out using rotary aircraft with a cost of less than $5,000. Largely, UAS construction inspections fit into one or more of these categories: erosion control, construction progress, construction QA/QC, and structures.

EROSION CONTROL

Key UAS Characteristics: Obstacle avoidance for flying low and adjacent to trees or structures and longer battery life for large sites

A 2015 study conducted by Auburn University concluded that aerial images gathered by UAS provide an advantageous and unique perspective that allow quick and easy identification of problems areas such as rill erosion (removal of soil by surface water running through little streamlets or abrupt vertical drops, also known as headcuts or knickpoints, in the stream bed into deeper, faster-flowing channels). The researchers found aerial images to be useful in determining the source of eroded material (Perez et al. 2015).

In North Carolina, both contractor and DOT crews have successfully completed UAS inspections of erosion control measures on highway projects. Typically, these inspections are being performed using relatively low-cost, entry-level, commercial UAS with a retail price under $2,000.

The use of small UAS can increase productivity and improve inspection quality. Some of the benefits include the following:

- Access to difficult locations by air, instead of traversing soft, slippery ground, to reduce inspector fatigue and hazard exposure
- The ability to quickly scan long distances of silt fence without having to walk each segment
- Access to the center of large retention facilities to inspect risers, baffles, and other critical components (see Figure 3)
- The generation of highly effective record keeping in video and digital image format that allows the quick and efficient conveyance of discrepancies
- Inspection of construction and repairs that limits exposure to trench and excavation hazards for the inspector
- Final inspection of difficult to observe features after establishment of vegetation and wildlife hazards

In some cases, large complex sites that took an entire day to inspect are now being completed in a matter of hours. In addition, personnel are able to access areas that might otherwise be inaccessible.

Assuming an average inspector loaded rate of $75 per hour with 50 rain events per year, a two-year project could expect an approximate labor-hour savings of $10,000. Figure 4 represents a typical two-year project.

The payback period on the initial investment is approximately 35 inspections. This does not include the savings from decreased exposure to site hazards.

NCDOT

Figure 3. UAS images of retention ponds

CONSTRUCTION PROGRESS

Key UAS Characteristics: Large sensor-based camera and adjustable focal length for high definition orthomosaics and detailed still images

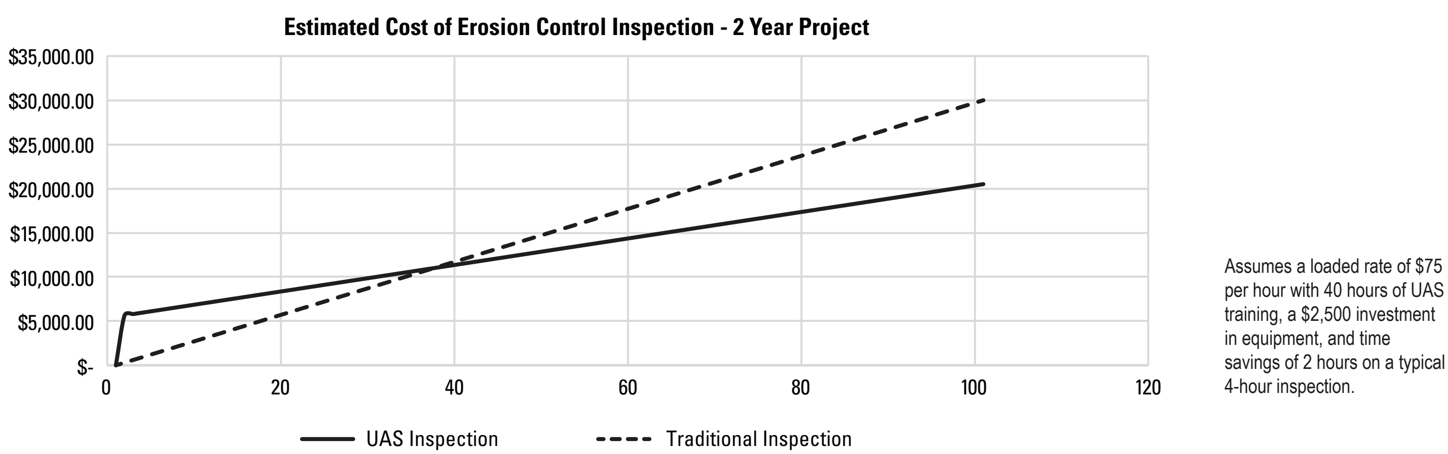
Monitoring construction progress, verifying pay applications, and maintaining schedules can be difficult and time-consuming. Using a UAS, a single operator can streamline this process while providing a more complete record (see Figure 5).

UAS images and videos can be used to verify progress for pay applications and project milestones and create accurate representations for tracking and calculating liquidated damages and responding to claims.

Site photos can be combined to create site-wide, high-resolution imagery in what is called an orthomosaic. In an orthomosaic, high-resolution images are taken in an overlapping and usually automated fashion using a built-in or third-party application. Images are stitched together using the automated collection application or can be stitched together using cloud and desktop software.

NCDOT

Figure 5. Construction progress on a flyover bridge

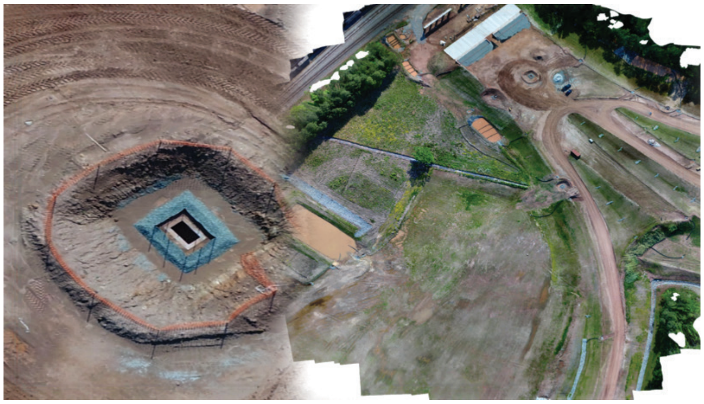


FHWA

Figure 4. Estimated cost of erosion control inspection with UAS vs. traditional

Completed files are available in native image formats or georeferenced formats for geographic information system (GIS) applications. Figure 6 shows a sample orthomosaic stitched using commonly used software and captured using a prosumer UAS.

Collection of the images in Figure 6 was completed in approximately 15 minutes onsite. The image on the left is a full resolution crop of the image on the right.



Images from Paul Rogers

Figure 6. UAS orthograph images

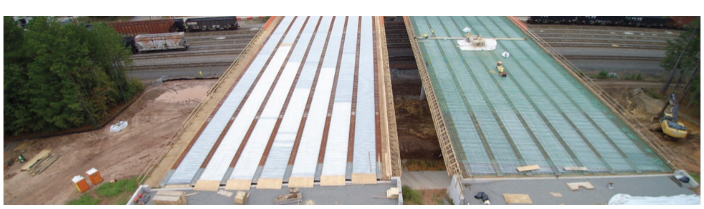
Orthographs are georeferenced and can be used to update satellite imagery in Google Earth or other GIS platforms and are easily shared with project teams. Operators can create a site-wide image map on a weekly or monthly basis to create a permanent record on a construction timeline. These records allow the verification of as-builts during expansion and repair projects in the future.

Pay Verification

UAS images provide a quick and precise way to account for material line item costs. Some of these items include the following:

- Prefabricated members – steel beams, precast sections
- Traffic control – cones and delineators, barricades, signage
- Stockpile materials – base course, fill, ballast stone, recycled materials
- Embedded materials – reinforcing steel, dowel bars, conduit (see Figure 7)
- Embankment/borrow quantities
- Clearing and grubbing

Aerial images do not replace field verification procedures but can help provide context and perspective.



NCDOT

Figure 7. Bridge reinforcing steel as viewed from a UAS

CONSTRUCTION QA/QC

Key UAS Characteristics: A zoom camera (adjustable focal length) for detail clarity and infrared cameras for hot-mixed asphalt and surface treatments

UAS will likely never replace boots on the ground inspections. The skilled inspector deduces, reasons, and uses a variety of senses to get the total picture in each situation; however, conveying these details can often be difficult. Aerial perspectives provide unique context to offsite engineers and projects managers.

UAS can help save time inspecting large areas while helping to verify that discrete testing is representative of the project. In highway construction, UAS can be used to quickly look for segregation in new hot-mixed asphalt (HMA) and for dowel bar placement in Portland concrete. Tasks that generally require head down concentration near equipment or adjacent to traffic can be completed from a safe location in line of the site.

UAS also allow the inspector to augment routine inspection tasks and collect a real-time aerial perspective that provides context to a current situation. Issues discovered during routine inspections can be viewed from an aerial perspective, allowing recognition of patterns.

Some sites can be difficult to observe from the ground. In pavement surface treatments, UAS are being used to check application consistency, coverage and overlap, and aggregate placement. The construction process of many surface treatments can be difficult to inspect on foot or by vehicle.

UAS allow inspectors to monitor and log activities over a long stretched out site without constantly having to reposition, allowing more time to be focused on inspection. In North Carolina, for example, chip seals and asphalt rejuvenation projects have been successfully inspected on highways and at airports.

Surface Treatments

Equipped with a thermal camera, UAS have been successfully used to locate thermal segregation in HMA pavement projects while staying clear of the placement and compaction operations. Infrared cameras are also successfully being used to observe application temperature and consistency in surface treatments and application consistency in pavement markings (see Figure 8).

When the applied materials are a different temperature than the base pavements, the pavement and material temperature move toward the same temperature.

Figure 8. UAS surface treatment inspection (visible and IR)

Thinner applications will have less stored thermal energy than thick applications and will change temperature at a different rate. These areas are easily identifiable using a UAS-mounted thermal camera. In these fast-paced construction activities, UAS provide a unique perspective on materials, processes, progress, and the end product.

Low-end infrared thermal cameras run approximately $2,000; whereas, mid-range cameras quickly approach $10,000.

Safety Inspections

In many jurisdictions, Occupational Safety and Health Administration (OSHA) and jobsite safety inspection are expected to be conducted as part of the onsite QA/QC teams' daily duties. With the use of a UAS, inspectors and engineers can view a variety of construction scenarios without being directly exposed to the hazards or getting in the way of production.

For example, UAS have been used to document jobsite safety violations and to provide inspections of unsafe excavations. On resurfacing jobs, UAS have also been successfully utilized to verify lane-closure configurations and attenuator spacing for the safety of both workers and motorists in work zones.

Quality of Pavement Markings

Pavement markings are a significant part of construction and maintenance projects, but they are often overlooked as projects are coming to end. Color and retroreflectivity can be measured using a variety of portable and vehicle-mounted instruments. Size and geometry verification of individual markings is often done by hand and occasionally by survey. However, many projects are impractical to see from a single vantage point, making it difficult to check alignment for conformity to the plans.

Oblique and top-down images allow for the best perspective when verifying marking layout, alignment, and consistency. The images are easily captured using an inexpensive UAS (see Figure 9).

Inspection Training

The unique perspectives that UAS provide are also becoming instrumental in developing media for demonstrating construction processes. Aerial images and video footage can be used to highlight common issues and show how to identify these issues; perhaps just as important, the images and video can help keep the attention of inspectors and contractors during training.

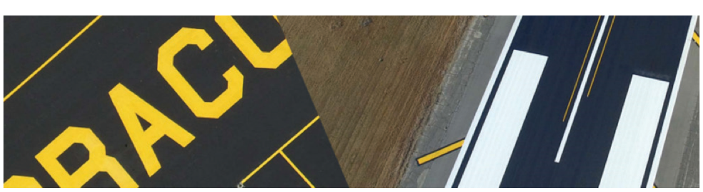


Figure 9. Airfield marking inspection

For many agencies, work has begun to create updated training materials for inspection tasks as the popularity of UAS increases. For example, UAS stills and video documentation from surface treatment inspections are being transformed to train new hires and contractors in hopes of combating a rapidly retiring workforce. In the private sector, UAS video is being utilized to train airfield inspectors about runway markings from a new perspective.

STRUCTURE EVALUATION

Structural evaluation by UAS is one of the fastest developing regions of infrastructure inspection. In bridge construction, UAS are capable of providing inspection in difficult to access locations using significantly less equipment and in significantly less time. The location of segregation in concrete structures or verification of puddle welds, shear studs, and bolted connections in steel structures can be completed quickly and safely using a UAS with a high-resolution camera.

CONCERNS AND LIMITATIONS

Weather can be a constraint with timely UAS construction inspections. A site may need to be inspected, but high winds and rain limit the abilities to do UAS inspections. Although aerial images will always be weather dependent, the UAS can be quickly deployed as soon as weather permits.

Flying in wind can deplete the UAS battery faster than normal. Wind makes it more difficult to keep control and can impact image quality. Cold temperatures, rain, and extreme heat can also be detrimental to UAS components.

Another consideration is the time of day the flights are being performed. The angle of the sun can prevent inspecting specific site objects or areas due to glare or shadows.

CONCLUSIONS

Both the affordability and capabilities of small UAS have dramatically improved. Construction inspection UAS primarily consist of "off-the-shelf" units in the $2,000–$5,000 price range. Despite unique project inspection needs, many platforms work well in multi-role missions.

UAS have proven to be an effective tool in transportation infrastructure construction inspection. UAS have reduced inspection time, improved inspection effectiveness, decreased the cost, and improved inspection safety.

REFERENCES

Perez, M. A., W. C. Zech, and W. N. Donald. 2015. Using Unmanned Aerial Vehicles to Conduct Site Inspections of Erosion and Sediment Control Practices and Track Project Progression. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2528, pp. 38–48.

Zainudin, A. Z. B. 2015. Application of Drone in Visual Inspection for Construction Project. Bachelor's thesis. University Malaysia Pahang.

ONLINE RESOURCES

Electronic Code of Federal Regulations Title 14: Aeronautics and Space, Subchapter F, Part 107—Small Unmanned Aircraft Systems. https://www.ecfr.gov/cgi-bin/text-idx?SID=dc908fb739912b0e6dcb7d7d88cfe6a7&mc=true&node=pt14.2.107&rgn=div5.

Federal Aviation Administration (FAA) Unmanned Aircraft Systems (UAS). https://www.faa.gov/uas/.

Federal Highway Administration (FHWA) Unmanned Aerial Systems (UAS). https://www.fhwa.dot.gov/uas/.

FHWA Center for Accelerating Innovation Every Day Counts-5 (EDC-5): Unmanned Aerial Systems (UAS). https://www.fhwa.dot.gov/innovation/everydaycounts/edc_5/uas.cfm.

Tech Brief

USE OF SMALL UNMANNED AERIAL SYSTEMS FOR BRIDGE INSPECTION

INTRODUCTION

The capabilities of unmanned aerial systems (UAS) have improved exponentially over the past few years due to advances in the technology; lower prices, which have made UAS more widely available; and greater overall awareness of the technology, which has opened UAS to new uses. This progress has resulted in user-friendly equipment that can fly autonomously, avoid obstacles, and perform repeatable flights in areas that are sometimes difficult to access.

Given these capabilities, the overall use of UAS for infrastructure inspection and condition monitoring activities continues to increase. In a March 2018 survey by the American Association of State Highway and Transportation Officials (AASHTO), 35 of 44 reporting state departments of transportation (DOTs) indicated that they have experience deploying UAS in some capacity (AASHTO 2018a).

Inspection of in-service bridges (Figure 1) are one of the more promising potential uses of UAS.

The agility and overall capabilities of UAS can be leveraged to alleviate several barriers or challenges inherent in the bridge inspection process, including the high cost and limited availability of specialized access equipment, limited inspector access to portions of a bridge, and the cost and safety implications of the traffic restrictions needed for some inspections.

UAS are already used by other industries to capture data in challenging environments, monitor weather, control traffic, support firefighters, map stockpiles, conduct surveys, and perform other tasks.

https://www.fhwa.dot.gov/innovation/everydaycounts/edc_5/docs/uas-factsheet.pdf

Figure 1. Use of UAS for in-service bridge inspection

Current bridge inspection methods rely primarily on visual and hands-on evaluation techniques performed by inspectors. For visual observations to be effective, inspectors must be able to see all of the elements of the bridge to properly assess their conditions. To effectively see some elements, certain types of access equipment may be needed. For a hands-on inspection to investigate suspected deterioration, inspectors rely on a combination of access equipment (ladders, rigging, scaffolds, and rope) and vehicular lifts (man-lifts, bucket trucks, and under-bridge inspection vehicles). UAS have the potential to help inspectors quickly and safely see bridge components that are difficult to reach and provide useful information that can help inspectors determine whether additional, more detailed inspection is needed. UAS can potentially improve the bridge inspection process in several ways:

- Allow inspectors to gain closer access to elements traditionally viewed through binoculars
- Improve safety for inspectors
- Improve safety for the public through fewer lane closures
- Lower overall inspection costs
- Provide unique and cutting-edge deliverables, such as digital image capture and analysis

A large body of local and international research is available on UAS inspections, and DOTs in several states have incorporated UAS into regular activities and sponsored research dating back over a decade. As early as 2008, the California DOT (Caltrans) and the University of California experimented with a tethered electric ducted fan UAS. More recently, the DOTs of Florida, Idaho, Michigan, Minnesota, and Oregon have conducted and/or sponsored studies into the use of various UAS platforms for bridge inspections with varying levels of success.

ADVANTAGES OF UAS FOR BRIDGE INSPECTIONS

A report requested by the American Association of State Highway and Transportation Officials (AASHTO) and sponsored by the National Cooperative Highway Research Program (NCHRP), *Successful Approaches for the Use of Unmanned Aerial Systems by Surface Transportation Agencies* (Banks et al. 2018), considered a state agency's UAS program successful if it yielded one or more of the following results:

- Increased safety or reduced liability for inspections
- Increased efficiency and productivity of inspections, or reduced impact on the public
- Increased cost savings for inspections
- Increased environmental protection during inspections
- Produced higher quality end products for inspections

Ultimately, a thorough understanding of UAS technology coupled with creative implementation provides an opportunity for UAS to revolutionize the way surface transportation agencies perform bridge inspections.

BRIDGE INSPECTIONS

The National Bridge Inspection Standards (NBIS), found in the Code of Federal Regulations (23 CFR 650 Subpart C), define the regulations for the inspection and evaluation of all publicly owned bridges. The AASHTO *Manual for Bridge Evaluation* (MBE) (AASHTO 2018b) is incorporated by reference into the NBIS along with other related documents, such as the *Bridge Inspector's Reference Manual* (BIRM) (Ryan et al. 2012). According to the MBE, seven types of formal inspections are conducted on publicly owned in-service bridges: initial/inventory, routine, in-depth, fracture-critical members, underwater, special, and damage.

Inspection procedures outlined in the MBE require that a team leader who meets minimum qualifications as stated in CFR 650.309 is required to be on site for all the inspection types listed according to the NBIS, except for damage or special inspections, for which qualification is usually dictated by state policy. Because a team leader must be present for all inspections, inspections, they are ideal candidates for UAS remote pilots. These bridge inspectors can take advantage of their technical understanding of bridge structures while also appreciating the limitations of the standard inspection approach.

The following sections describe the roles that UAS might play in each of the seven types of formal bridge inspections listed in the MBE.

Initial/Inventory

On completion of bridge construction, a UAS could capture imagery from multiple perspectives to establish a more robust baseline condition of the bridge. Specifically, a three-dimensional (3D) image (Figure 2) and point cloud of the as-built structure can be developed to supplement standard two-dimensional (2D) photographic documentation, Additionally, the UAS can record its own flight paths so that they can be repeated in future inspections for direct comparison.

Wells and Lovelace 2017, MnDOT

Figure 2. 3D model created from images of a completed bridge captured by UAS

Routine

Every 24 months or as required, a UAS could obtain imagery during a routine inspection that cannot otherwise be captured, getting closer to certain areas than would be possible with traditional inspection and repeating previously recorded flight paths while taking images that can be compared with previously acquired images from the same vantage point. Technological advances also allow for the use of thermal cameras to check for subsurface anomalies, all the while minimizing traffic disruptions and improving the safety of the inspector and the public.

In-Depth and Fracture-Critical Members

The NBIS currently requires hands-on inspections by an inspector for all critical elements of a bridge during a fracture-critical inspection. Although currently available UAS are not yet capable of contributing significantly to hands-on inspections of this nature, technologies such as hyperspectral imaging (Figure 3) are evolving and may soon be available to perform remote nondestructive testing.

Although UAS are not currently acceptable as a replacement for hands-on inspections, at a minimum, UAS can assist in these inspections by providing initial images of difficult access areas and serve to supplement images captured by the bridge inspector performing the hands-on inspection.

Underwater

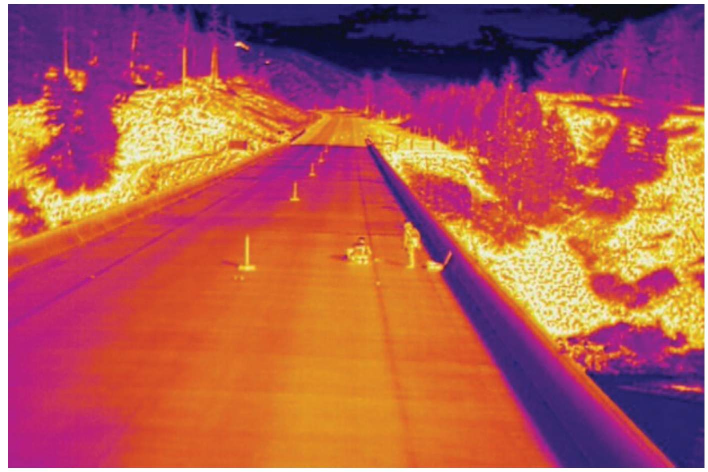
As their capabilities improve, remotely operated underwater vehicles may eventually be used in the field to perform underwater bridge inspections. In limited visibility conditions, underwater divers must manually feel their way around the bridge structure to locate potential deteriorated areas. Underwater vehicles with active sonar capabilities could assist in hazardous situations, such as high flows and poor visibility, by providing better representation of the structure and allowing divers to gather information prior to entering the water and focus on the areas noted. At present, UAS are primarily being used to remotely evaluate water flow around structures, which can assist in inspection planning.

Special

A UAS could provide an economical means of monitoring a known defect without the need for specialized access equipment and allow for a comparison of imagery on a regular basis.

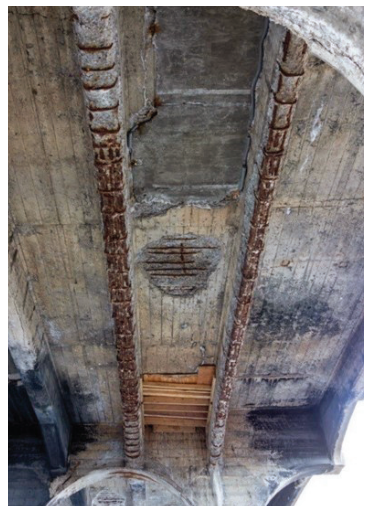
Damage

An unscheduled inspection to assess structural damage (Figure 4) from either environmental events (e.g., flooding) or human action (e.g., truck impacts) is an excellent use case for a UAS.



Wiss, Janney, Elstner Associates, Inc.

Figure 3. Infrared image captured by UAS



Wiss, Janney, Elstner Associates, Inc.

Figure 4. Damage captured by UAS

UAS PLATFORMS AND SENSORS

UAS technology is ever-changing, but the current state of the practice for bridge inspections favors the use of multirotor rather than fixed-wing aircraft. The multirotor aircraft described in the remainder of this tech brief can fly autonomously or be controlled remotely and can be equipped with global positioning system (GPS) sensors, a barometer, and one or more inertial measurement units (IMUs).

A multirotor UAS equipped with an IMU that electronically measures orientation, velocity, and gravitational forces using accelerometers, gyroscopes, and often magnetometers is essential for safe and controllable flight. The aircraft's sensors communicate with the onboard microcontroller, which relays sensor information along with the video feed from the onboard cameras or sensors to the remote pilot, enabling stable, close-range bridge inspections.

The multirotor UAS available to the bridge inspection market can be broken into three categories based on the systems' configurations (and the price ranges shown in Table 1) as follows:

- Compact systems with a fixed camera and sensor suite
- Intermediate systems with interchangeable proprietary cameras, lenses, and sensors
- Advanced systems that are only limited in terms of the possible camera and sensor options by weight, type of use, and unique sensor configuration

Additional information regarding these categories is provided in Table 1.

CONTROL AND SOFTWARE

UAS operate internally on proprietary firmware but can usually be either controlled remotely by a pilot or pre-programmed with a set flight path. Data can be captured manually or at set intervals using proprietary or third-party software. Most of the branded UAS can be operated using a mobile device through applications that operate on both the Apple iOS and Android platforms.

Flight Control Software

Most UAS come equipped with their own branded control applications, but many third-party applications that operate as effectively as the branded software can be installed depending on flight requirements or user preferences. This third-party software can be a substitute for either the existing remote flight control or autonomous flight planning and control software.

Live Image Processing

The images captured by the UAS are transmitted back to the remote controller, which is typically connected to a mobile data collection device running iOS, Android, or a similar platform. The data collection device allows for live image processing, including but not limited to the simultaneous review of still images either on a separate on-site monitor or via streaming over the internet.

Some applications use the computing power of the remote mobile device to stitch the images together to provide for an overall picture of the area covered by the UAS. Other software allows the pilot (or inspector via a live video feed) to annotate and tag portions of the images in real-time for later automated reporting, which helps reduce the time required for image post-processing.

Image Post-Processing

For image post-processing, UAS inspections generate a large amount of data and agencies need to plan how to manage these large datasets. A process flow needs to be established by the agency to outline processing, storage, and archival, which may require special expertise within the program.

Table 1. Multirotor UAS available for bridge inspection

Details	Compact	Intermediate	Advanced
Image			
Weight	1–4 lbs	5–10 lbs	2–55 lbs
Rotors/Size	4 rotors; often able to be folded into a small, convenient carrying size	4–6 rotors; typically not foldable and requires dedicated carrycase	4 or more rotors; usually larger than intermediate models
Sensors	3-axis gimbal-mounted camera, with or without zoom capability, using a complementary metal-oxide semiconductor (CMOS) sensor up to 1 in. in size that can store an effective 12–20 million pixels (12–20 megapixels) in still photos or capture up to 4K of video at a maximum bitrate of 100 Mbps	Similar to a compact model with the addition of infrared sensors and additional options for proprietary cameras and lenses for better image capture with CMOS sensors 1 in. or greater; some models have separate controls for flying and image capture, with the cameras utilizing a gimbal that can pan and tilt	Ability to either perform specialist functions or be equipped with a multitude of different cameras and sensors depending on requirements, e.g., light detection and ranging (LIDAR), hyperspectral imaging, and ground penetrating radar
Flight Time	20–30 minutes	15–30 minutes	8–35 minutes
Cost	$800–$2,500	$2,500–$10,000	$5,000+

Once the images have been downloaded from the UAS, an extensive array of software is available to process the data for different uses:

- *Photogrammetry*, the science of taking measurements from photographs, allows image data from the UAS to be combined with accurate GPS coordinates to produce extremely accurate measurements from the images. The flight images obtained from the UAS have a large amount of overlap, and algorithms within the image processing software can identify related features in each image that allow the images to be joined (i.e., stitched) together.

  In addition to the stitching process, the software geometrically blends the overall image to remove distortions stemming from topographic relief, lens distortions, and camera tilt while creating a uniform scale. These large-format post-corrected images, which are referred to as orthomosiacs, provide the bridge inspector or bridge reviewer with accurate measurements and a detailed image of the overall structure while retaining the ability to zoom in on defects.
- *Radiometric infrared* software allows images to be calibrated to identify small differences in surface temperature.
- *Digital terrain modeling* uses algorithms to emulate the terrain while ignoring vegetation, while *digital elevation modeling* operates similarly but incorporates plant life. In both types of modeling, contours can be accurately mapped, stockpiles can be measured, and area and length can be evaluated.
- *Computer-aided design (CAD) file rendering* from point cloud data can be utilized to create drawings, take accurate measurements, and/or capture details of specific components.
- *3D modeling* allows multiple images and/or LIDAR points to be stitched together to form a “lifelike” image of the bridge structure. Software for 3D reality mesh modeling is available as a cloud service or as standalone desktop programs. The images produced by the software can be rotated to provide a greater understanding of the structure’s elements and to help visualize potential issues and identify surface anomalies within the context of the surrounding elements in the structure.

  Viewing the structure in three dimensions allows all interested parties to gain a much greater understanding of the complexities involved in bridge structures. Although the current accuracy of aerotriangulation does not consistently allow for perfect visual results, some software packages allow back referencing to the original image or images from which the 3D model was created.

FAA REGULATIONS REGARDING UAS FOR BRIDGE INSPECTIONS

UAS operators in both the public and private sectors must adhere to statutory and regulatory requirements. Public aircraft operations (including UAS operations) are governed under the statutory requirements for public aircraft established in 49 USC § 40102 and § 40125. Additionally, both public and civil UAS operators may operate under the regulations promulgated by the Federal Aviation Administration (FAA).

The provisions of 14 CFR Part 107 apply to most operations of UAS weighing less than 55 lbs. Operators of UAS weighing greater than 55 lbs may request exemptions to the airworthiness requirements of 14 CFR Part 91 pursuant to 49 USC § 44807.

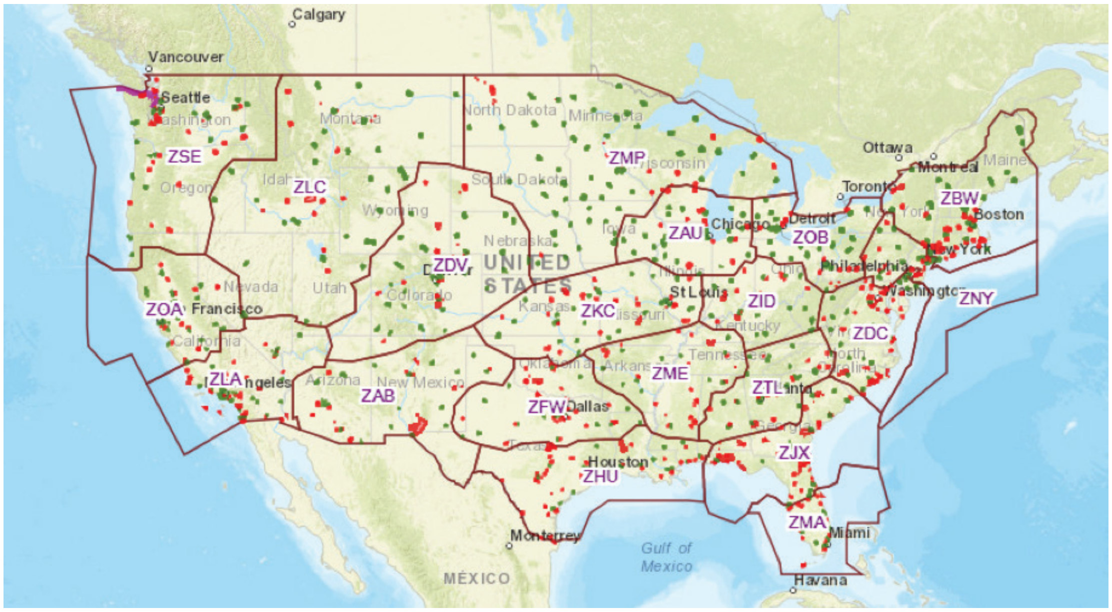
UAS operators should also be aware of the requirements of the airspace in which they wish to fly. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/.

Because the height of a bridge above ground level seldom exceeds 400 ft, altitude is not the primary limitation; many bridges are located in controlled or restricted airspace, and it is the responsibility of the UAS pilot to understand and follow the regulations set by the FAA, including the UAS registration requirements, airspace authorizations, and specific waiver requests.

Airspace Authorizations

The National Airspace System (NAS) is the network of US airspace, navigation facilities, services, and airports with their associated technical information, rules, regulations, policies, procedures, personnel, and equipment, which is shared jointly between the FAA and the military. The use of a UAS within this system requires knowledge and understanding to safely operate within the requirements. Most airspace is unrestricted, but to assist UAS operators, the FAA and its partners provide the following resources:

- Low Altitude Authorization and Notification Capability (LAANC) system (https://www.faa.gov/uas/programs_partnerships/data_exchange/)
- FAADroneZone unmanned aircraft registration and links to forms (https://faadronezone.faa.gov)
- UAS Facility Maps (https://www.faa.gov/uas/commercial_operators/uas_facility_maps/)
- B4UFLY mobile application for drone operators (https://www.faa.gov/uas/recreational_fliers/where_can_i_fly/b4ufly/)



Green dots = airports participating in the LAANC; Red dots = airspace that requires a manual or online application

Figure 5. FAA UAS facilities map

Under the FAA UAS Data Exchange umbrella, LAANC is a collaboration between the FAA and industry that directly supports UAS integration into the airspace. It provides access to controlled airspace near airports through near-real-time processing of airspace authorizations below approved altitudes in the controlled airspace.

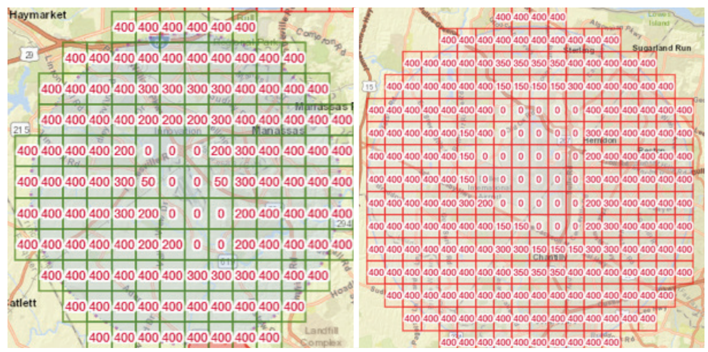
Through its platform partners, LAANC provides UAS pilots with the ability to apply for and receive online approval to fly up to the prescribed altitudes under 400 ft according to the grid pattern in the controlled airspace and to request permission to fly above the altitude ceiling in a particular grid, which is coordinated manually by the local air traffic control (ATC). This authority can be sought up to 90 days prior to the flight date.

In order to assist operators in controlled airspaces, the FAA publishes facility maps with details on towered airport locations (see Figure 5) where the FAA may grant permission to fly at maximum altitudes.

A facility map provides pilots with information concerning specific restricted airspace. A closer view of any of the green or red dots in Figure 5 reveals the five-mile radius around an airport, laid out in a grid pattern, as shown in Figure 6.

Around the runway and adjacent to the airport, the grid altitude is 0 ft. As the radius increases, the allowable altitude a UAS may fly increases in 50 to 100 ft increments, depending on aircraft flight paths and other requirements specific to the airport.

LAANC is available at nearly 300 air traffic facilities covering about 500 airports. If pilots need to fly in controlled airspaces near airports not offering LAANC, they can use the manual process to apply online for an authorization via the website.



Green = permission obtained through LAANC; Red = permission obtained through a manual or online application

Figure 6. Example of FAA UAS facilities map data

The B4UFLY mobile app gives all UAS operators a comprehensive overview of all airspace and other limitations that apply to recreational as well as commercial operators. It includes information that may not limit flight, but that could be of use to commercial operators.

UAS LIMITATIONS

A UAS is an aircraft that is usually electromechanical powered; lightweight (.55 to 55 lbs); limited in terms of flight time (unless tethered) and distance; sensitive to weather (including difficulty in higher winds, not to mention inclement conditions), stray currents, and magnetic or radio frequency interference; controlled by radio frequencies or pre-programmed GPS flight coordinates that require contact with the controller and the GPS and/or global navigation satellite system (GNSS) signal; and restricted in its use by federal and local law.

UAS inspections of bridge structures has its challenges that need to be considered when planning an inspection. At a minimum, the following limitations should be reviewed:

- Pedestrian and vehicular traffic need to be considered as well as other safety and flight restrictions.
- While recognizing the complexities of flying in congested areas such as trusses or under bridge structures, flight paths need to be carefully considered to accommodate single battery flight times, which are generally about 20–30 minutes.
- An unaided visual line of site of the UAS by the remote pilot or visual observer is required at all times during inspections, so understanding site access and other limitations to visual lines of site should be considered (see the FAA Fact Sheet on Small Unmanned Aircraft Regulations [Part107] Operating Requirements section at https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=22615).

Recognizing the limitations of UAS is as important as understanding the benefits they provide to bridge inspections.

CONCLUSIONS

UAS offer a number of potential advantages for some bridge inspection activities, in that they can make it easier for inspectors and engineers to see the most difficult to reach sections of bridges at almost any time with a little planning and preparation, but on relatively short notice. Moreover, the use of UAS puts fewer workers at risk because it reduces the need for workers to climb to high, dangerous, and difficult-to-reach bridge areas as frequently.

UAS are not intended to replace bridge inspectors, but rather can be used as a tool to supplement the information available to inspectors and bridge owners and provide better access to information on the condition of a bridge and its elements.

REFERENCES

AASHTO. 2018a. 35 State DOTs are Deploying Drones to Save Lives, Time and Money. American Association of State Highway and Transportation Officials, Washington, DC. News Release, March 27. https://news.transportation.org/Pages/NewsReleaseDetail.aspx?NewsReleaseID=1504.

AASHTO. 2018b. *Manual for Bridge Evaluation, 3rd edition*. American Association of State Highway and Transportation Officials, Washington, DC.

Banks, E., S. J. Cook, G. Fredrick, S. Gill, J. S. Gray, T. Larue, J. L. Milton, A. Tootle, P. Wheeler, P. R. Snyder, and Z. Waller. 2018. *NCHRP Scan 17-01: Successful Approaches for the Use of Unmanned Aerial Systems by Surface Transportation Agencies*. Arora and Associates, P.C., Lawrenceville, NJ. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-68A_17-01.pdf.

Electronic Code of Federal Regulations Title 14: Aeronautics and Space, Subchapter F, Part 107—Small Unmanned Aircraft Systems. https://www.ecfr.gov/cgi-bin/text-idx?SID=dc908fb739912b0e6dcb7d7d88cfe6a7&mc=true&node=pt14.2.107&rgn=div5.

Ryan, T. W., J. E. Mann, Z. M. Chill, and B. T. Ott. 2012. *Bridge Inspector's Reference Manual*. FHWA-NHI-12-049. National Highway Institute and Federal Highway Administration, Washington, DC.

Wells, J. and B. Lovelace. 2017. *Unmanned Aircraft System Bridge Inspection Demonstration Project Phase II*. Minnesota Department of Transportation, St. Paul, MN.

ASTM RESOURCES

ASTM F3178-16 Standard Practice for Operational Risk Assessment of Small Unmanned Aircraft Systems (sUAS).

ASTM F2909-14 Standard Practice for Maintenance and Continued Airworthiness of Small Unmanned Aircraft Systems (sUAS).

For Personnel

ASTM F3266-18 Standard Guide for Training for Remote Pilot in Command of Unmanned Aircraft Systems (UAS) Endorsement, which, in addition to the FAA knowledge test, advocates which practical skills should be able to be demonstrated for proficiency.

Proposed New Standards under Development

ASTM WK62741 Guide for Training UAS Visual Observers.

ASTM WK61764 Training for Public Safety Remote Pilot of Unmanned Aircraft Systems (UAS) Endorsement.

Tech Brief

USE OF SMALL UNMANNED AERIAL SYSTEMS FOR EMERGENCY MANAGEMENT OF FLOODING

INTRODUCTION

Flooding is a unique event or occurrence: it may be a standalone incident, or it may accompany another event. As examples, a hurricane may produce flooding as well as wind damage, or a landslide may dam a river and create a flood. Flooding events are unique in terms of their scale of occurrence or time.

There is likely some warning prior to a flooding event, and flooding is generally a long duration event, when it can be weeks or months before flood dangers subside. The event may be a series of floods, with a flood from initial intense rain directly falling in the affected area, followed by river flooding from drainage or upstream rain moving into the area, as seen with Hurricane Harvey in the metropolitan Houston, Texas, area.

Flooding impacts can be gradual or sudden, such as the levee breach in New Orleans, Louisiana, with Hurricane Katrina in 2005.

Flooding poses immediate threats to personal safety and infrastructure, along with general risks of hazardous material leaks or spills. Flooding may as also result in search and recovery of missing persons.

A wide variety of unmanned aerial systems (UAS) have been used for flood events since at least 2005. UAS have been used by formal response agencies for at least 12 disasters from flooding or for events that had flooding associated with them. Following is a partial list, in chronological order, of UAS use in response to flooding, which notes how each response was able to utilize UAS differently to meet the specific needs of the event.

- Hurricane Katrina 2005. This was the first reported use of UAS. Both rotorcraft and fixed wing assets were used to determine the flood crest of the Pearl River in Louisiana and Mississippi and the risk to surrounding communities (Murphy 2014).
- Hurricane Wilma 2005. A rotorcraft UAS was used to examine the infrastructure including a bridge to Fort Myers Beach off the southwest Florida coast (Murphy 2014).
- Thailand Floods 2011. Fixed-wing UAS were used for general surveys of the flooding (Srivaree-Ratana 2012).

Center for Robot-Assisted Search and Rescue

Figure 1. Small UAS used by Fort Bend, Texas, Office of Emergency Management before, during, and after Hurricane Harvey flooding

- Oso, Washington Mudslides 2014. UAS were used to provide photogrammetric mapping of the mudslide, which was used to determine where to cut an emergency bypass flood channel (Murphy et al. 2015).
- Balkans flooding in Serbia 2014. UAS was used to survey the extent of the disaster and to actively investigate why drainage mitigations were not working (Cubber et al. 2014). The UAS found a pump set up by a farmer that would have been impossible to see from the ground.
- Blanco River, Texas, flood 2015. UAS were used by volunteers in Texas to conduct searches for missing persons swept away the flood into inaccessible areas (Murphy 2016).
- Louisiana Flood 2016. UAS were used by the Tangipahoa and Washington Parish Offices of Emergency Management to determine the extent of flood, impact on transportation infrastructure, and citizens at risk (Murphy 2016).
- Texas Memorial Day Flood 2016. UAS were used by the Fort Bend, Texas, Office of Emergency Management to monitor rising flood waters and predict flooding inundation (Murphy et al. 2016).
- Hurricane Harvey 2017. UAS were used extensively by the Fort Bend, Texas, Office of Emergency Management to support all emergency support functions with 112 flights before, during, and after the flood crest (Fernandes et al. 2018).
- Hurricane Florence 2018. The North Carolina Department of Transportation (NCDOT) used UAS to assess the extent of flooding on major roadways.
- Hurricane Michael 2018. UAS flights for general damage assessment captured unreported damage to a Florida bridge. UAS with thermal imagery was also used to search for missing persons presumed swept inland with debris.

Figure 1 shows most of the UAS used by the Fort Bend County Office of Emergency Management before, during, and after Hurricane Harvey. As shown in Figure 1, these UAS are small and portable.

The most commonly used platform, which was flown in 72 of the 112 missions at Hurricane Katrina and used extensively by NCDOT for Hurricane Florence, costs less than $1K, can be folded to fit in a jacket pocket, and can be recharged from a car inverter. This indicates that agencies can now afford to adopt small UAS.

This document is organized as follows. After covering Federal Aviation Administration (FAA) regulations, it presents the seven basic missions that can be performed by small UAS, and then describes which missions are useful for before, during, and after a disaster. After review of UAS responses to flooding events, this document summarizes the primary use cases.

FAA REGULATIONS

UAS operators in both the public and private sectors must adhere to statutory and regulatory requirements. Public aircraft operations (including UAS operations) are governed under the statutory requirements for public aircraft established in 49 USC § 40102 and § 40125. Additionally, both public and civil UAS operators may operate under the regulations promulgated by the FAA.

The provisions of 14 CFR Part 107 apply to most operations of UAS weighing less than 55 lbs. Operators of UAS weighing greater than 55 lbs may request exemptions to the airworthiness requirements of 14 CFR Part 91 pursuant to 49 USC § 44807.

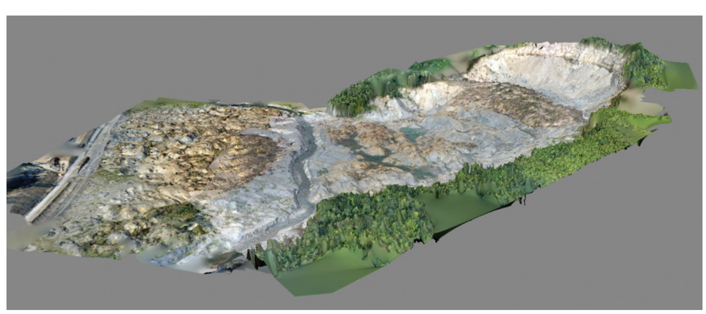
UAS operators should also be aware of the requirements of the airspace in which they wish to fly. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/.

THE SEVEN BASIC SMALL UAS MISSIONS

Following Fernandes et al. 2018, UAS missions can be divided into seven basic categories, as described below. UAS have been used for all seven categories for flooding events, although not all seven for a single event. Missions provide either images and video, digital elevation maps, or photogrammetric stitching of images into an orthomosaic image (see Figures 2 through 4).

Center for Robot-Assisted Search and Rescue

Figure 2. Video and imagery



Center for Robot-Assisted Search and Rescue

Figure 3. 3D digital elevation map

Center for Robot-Assisted Search and Rescue

Figure 4. Orthomosaic image

Note that photogrammetric stitching and elevation mapping require images to be gathered in sequences and viewpoints that are not amenable to real-time human comprehension.

Strategic Situation Awareness, Survey, and Reconnaissance

Strategic situation awareness (SA), survey, and reconnaissance consists of multi-purpose scans of the area. Depending on the specifics of the mission, the flights may be either real-time video and imagery or photogrammetric mapping. Typically, situation awareness favors a cinematic style of flying to give the viewer the sense of the area, while surveys and reconnaissance favor specific paths (e.g., lawnmower scans, follow a river).

Figure 5 shows a lawnmower scan path for a UAS to follow to gather images for a photogrammetric map of a neighborhood affected by Hurricane Harvey.

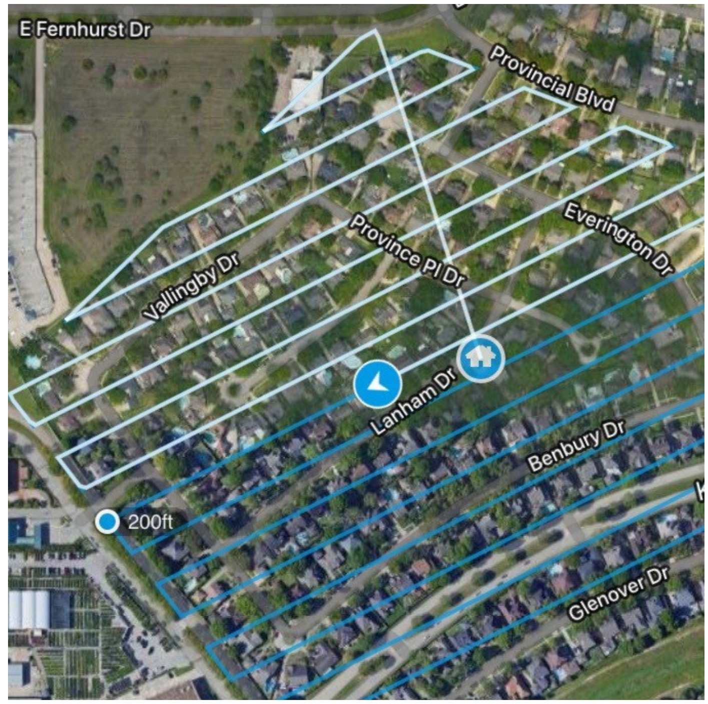
For floods, the objectives of this category of mission are to answer questions such as where's the flooding? How bad? Are people in distress? What is the state of the transportation infrastructure, roads and bridges?

Another application is to identify easement and standing water conditions that prevent power utility crews from restoring electricity. Hazardous material leaks are a real concern; What's that sheen on the water? diesel? chemical? sewage? and where is it coming from? Are those propane tanks floating away?

Another use is to identify stranded livestock. Strategic SA can be used to inform the public about the flood, the impact on individuals or their relatives, or why evacuation orders are in place, especially if data are readily available on a social media site.

Detailed or Structural Inspection

The detailed or structural inspection mission is about experts examining built structures via either a quick look or a formal examination. One example is the examination of



Lines in blue=path generated by software planning package; lines in white=progress of the actual flight

Figure 5. Lawnmower scan path for a UAS over a neighborhood affected by Hurricane Harvey

levees for signs of overflow (over the top) or for seepage (indicating incipient collapse). The most informative imagery is dependent on the structure and damage, and thus it is helpful to have an expert with the UAS team to direct the flight.

The flight may require more elevation (oblique) views than plane (nadir) views. Three-dimensional (3D) reconstruction is generally not used for the quick assessment.

This type of inspection is generally performed 10 feet (3 meters) away from the structure, which can be very challenging due to poor global positioning system (GPS) signals and wind shear. While some platforms have obstacle avoidance mechanisms, these mechanisms may be unreliable in such challenging conditions.

Ground Search and Rescue

In this mission, the UAS is generally assisting with the search for a missing person, object, or scene that is on the ground. In a flooding event, victims may have been swept away by the flood and the ground search is conducted after the waters have receded. For this mission type, high-resolution images are the most valuable, as video may be too difficult to freeze frame or lose resolution when paused.

A thermal payload may not be a silver bullet for finding either a survivor or a body, because foliage blocks any infrared signal. It is also important to note that imagery must be geotagged so that responders can go to the right location after the fact. In general, it is difficult for people or computer programs to interpret images.

The altitude at which an image was taken and the field of view (FOV) of the camera are necessary to understand the resolution and scale of objects in an image. Unfortunately, while most UAS systems embed the geographical coordinates of the UAS into the image, helpful attributes such as the altitude, FOV, and angle of the camera are not.

Water Search and Rescue

Water search and rescue is typically associated with a marine incident, although for a flood this includes a swift water rescue. A water search may be combined with a ground search for a victim after a boating accident on a lake where they possibly swam to shore, or a flood where a survivor may have been swept away but climbed out.

A missing person search in water requires high-resolution images. Thermal imaging may be the most reliable means to find a survivor in water, given that victims may present a small or partial profile and that waves and light reflection on the waves may confuse reviewers.

As with ground searches, any imagery must be associated with a geographical location, which is referred to as geotagging the image, so that responders can go to the right location; the altitude and FOV of the camera are also required to help with image analysis.

Debris, Flood Estimation, and Damage Assessment

Debris, flood estimation, and damage assessment is more detailed than general reconnaissance and more focused on documenting boundaries of an event, counting affected houses, and relating the current state of the area to the prior conditions. This type of assessment can enable drainage experts to confirm flood inundation maps and determine causes of variances (e.g., a fallen tree acting as a dam).

The mission might enable rapid volumetric estimations of debris after the flood recedes. It can also document land use and drainage issues to be resolved later.

This mission can be accomplished with real-time video and imagery (e.g., the drainage confirms that the flood boundary matches expectations) or with photogrammetric mapping for formal analysis of the extent of the flood.

Tactical Situation Awareness

Tactical SA uses a UAS to help the rescue team asses the condition of roads or bridges ahead to decide where to go from their current location. It also permits overwatch of teams or canines, or in swift water rescue oversight of floating debris that might jeopardize crews in boats, thereby increasing responder safety. Use of UAS for tactical SA is a common practice with the Florida State Emergency Response Team (SERT). UAS also has a place in traffic monitoring and detour routing efforts, providing needed viewpoints for transportation planning.

Delivery

This mission is for the UAS to facilitate delivery of material to any location. However, extreme care is needed when flying near people because operators tend to lose depth perception and may get far too close to objects and people. In addition, some platforms or payloads may not be able to maneuver safely for this mission type; something hanging off a small UAS changes the dynamics of the vehicle, creating a pendulum effect, so it may behave and move unpredictably.

MISSIONS BY PHASE

While the previous section introduced the seven categories of missions, it may be more helpful to think of these in terms of which missions appear during the disaster lifecycle. While there are many different models of disaster lifecycles, this document will use three phases: prevention/preparedness (before a flood), response and mitigation (during the event), and reconstruction and recovery (after evacuation orders are lifted). Table 1 lists the mission categories for each phase.

During the **Prevention/Preparedness** phase for a flood event, UAS can be used to periodically fly to establish conditions or can be flown immediately before a flood. Given the low cost of UAS, there may be no economic barrier to surveying areas every 3 months. In an area with a high rate of suburban development, frequent flights could allow agencies to become aware of potential problems while it is straightforward and cost-effective to fix.

Table 1. UAS missions by disaster phase

Prevention/Preparedness Before the Flood Crests	**Response and Mitigation** During the Flood Event	**Reconstruction and Recovery** After Evacuation Orders are Lifted
• Strategic Situation Awareness, Survey, and Reconnaissance • Detailed or Structural Inspection	• Strategic Situation Awareness, Survey, and Reconnaissance • Detailed or Structural Inspection • Debris, Flood Estimation, and Damage Assessment • Water Search and Rescue • Ground Search and Rescue • Tactical Situation Awareness • Delivery	• Strategic Situation Awareness, Survey, and Reconnaissance • Detailed or Structural Inspection • Ground Search and Rescue

While pre-event flights focus on geospatial attributes, such as the condition of drainage structures or use of the true state of the terrain to predict flood effects (Mardiatno et al. 2015, Özcan and Akay 2018), UAS with appropriate sensors can provide additional information. For example, they may soon be able to determine soil moisture (Dai et al. 2018), which, coupled with projected rainfall, should produce a more accurate prediction of flooding.

The primary missions for the Prevention/Preparedness phase are strategic SA, survey, and reconnaissance and detailed or structural inspection. Either mission may use real-time video or collect images for photogrammetric mapping.

During the **Response and Mitigation** phase for a flood, UAS can be used to reach areas that cannot be accessed by normal means, when satellite imagery would be too low resolution or takes days to obtain, or where manned aircraft would be too expensive. However, UAS do have limitations.

For example, as seen with Hurricane Harvey (Fernandes et al. 2018) and as noted by (Restas and Dudas 2013), UAS would not be able to fly in significant rain and thus cannot guarantee coverage. Another limitation is the flood itself may limit landing zones and thus prevent complete coverage with small UAS.

On the other hand, UAS offer many advantages. As shown with Hurricane Harvey (Fernandes et al. 2018) and the 2011 Thailand floods (Srivaree-Ratana 2012), UAS provided overviews of the extent of flooding and its impact. A UAS assisted in determining the fastest route to cut a bypass channel to relieve flooding from the Oso, Washington, mudslide (Murphy et al. 2015).

Cubber et al. 2014 were able to use a UAS to determine why flood mitigation was not working: a farmer was diverting the drainage system. Software can now segment floods from land, as research indicates (Gornea et al. 2016, Rahnemoonfar et al. 2018), which can help with planning.

The missions for the **Response and Mitigation** phase are likely to be flown with an expert due to the time pressure for actionable information. The missions are unlikely to involve photogrammetric mapping because moving water interferes with the image stitching process and because the operations tempo favors an "expert's eyes-on" strategy.

The missions are typically on the order of 8 to 12 minutes long, reflecting both a "see what you need to see; then, move on to the next important area" operations tempo and the limitations of flying within the visual line of sight.

The primary missions for the **Reconstruction and Recovery** phase are detailed or structural inspection and ground search, although there may be strategic SA, survey, and reconnaissance flights for the general public. Delivery has been discussed as a possible mission for sustaining communities that remain disconnected but has not been demonstrated in the US.

Using a small UAS to estimate the volume and type of household debris has been attempted, but trees interfere with the necessary views to make this practical; in addition, agencies may have existing contracts with firms to provide that assessment.

PRIMARY USE CASES

Primary UAS use cases for flooding events are summarized below.

Exploit low-cost UAS. Any mission that can be performed with a video camera can be conducted using a platform thatcosts approximately $1,000 and has 20–25 minutes of endurance. As shown in multiple responses, and especially Hurricane Harvey, missions have a short duration of 8–12 minutes as experts quickly see what they need to see in order to make a decision.

The smaller platforms have inexpensive batteries that can be charged from a car inverter rather than a generator. The small size of the UAS and the ability to carry multiple batteries and recharge while driving to the next location means that a team can carry two or more UAS in a vehicle for redundancy and work from dawn to dusk. Therefore, there is no compelling reasoning to buy a more expensive, longer endurance platform, especially for agencies just starting a program.

Consider the extent of coverage and types of missions needed before deciding on using a UAS over a manned asset. If there is a significant area to be covered, it may be more effective to use manned aircraft. While in theory, a UAS should be able to completely cover an entire area by flying a portion, then moving, flying, and so on, there may not be take-off and landing zones, especially for fixed-wing assets, for all sub-areas, or it may take hours to drive (or boat) from one sub-area to another.

Apply the COPIED heuristic to select the UAS platform for a mission. COPIED stands for **C**onstraints, **O**perator factors, **P**enetration or distance (e.g., visual line of sight), **I**nformation that the UAS provides to whom and when (e.g., video imagery streaming over FirstNet), the **E**nvelope in which the robot works (e.g., altitude, weather, expected range, density of manned assets), and the **D**uration (e.g., typical 8–12 minute missions or 30-minute mapping missions).

Fly before the flood crest to establish accurate "before" conditions. This can help update any topological data needed to project flooding. It can help identify potential vulnerabilities, such as new homes that may not have a flood-proof emergency route. UAS are such low cost, it should be possible to fly routinely in most areas.

Expect to use rotorcraft rather than fixed-wing UAS. Fixed-wing UAS often have very restrictive takeoff and landing zone requirements (e.g., an open, unflooded space the size of a soccer field). Rotorcraft can fly more reliably at lower altitudes and they can hover and stare, which is helpful in estimating the flow rate of flood waters.

Expect to fly within the visual line of sight in populated areas during the response and mitigation phase. Flights in urban and suburban regions will normally be visual line of sight for safety reasons; there is typically dense helicopter traffic, often below 200 feet. For example, life-flight helicopters may not waste time going up to a high altitude but instead zoom low and fast. Military, customs, and border patrol aircraft may also be operating at the tree line or running a river.

In densely populated airspace such as that seen with Hurricane Harvey, the UAS pilot will need a visual observer to keep a sharp look out for air traffic and have a plan for rapid descent to get out of the way. Rural areas see less helicopter air traffic due to the costs and logistics of getting a helicopter to fly to remote locations. However, being in a rural area does not guarantee a sparse airspace.

The missing person search after the Blanco River floods saw multiple private helicopters searching for signs of victims and flying under 100 feet, and the rural Oso mudslides were next to a military jet training route with pilots periodically deviating “one mountain over.”

Deploy a UAS from a boat or airboat, but with care. Boats are often the fastest way into a flooding disaster area. With Hurricane Harvey, this was extremely helpful in assessing the flooding impacts in the suburban mega-developments.

Send agency experts (and social workers) with the UAS team or prepare them to answer general questions. UAS are a magnet for the population; people will come over to find out what is going on and to ask questions about the response, how to get help, etc.

Even if there is cell coverage, it may be appropriate to have a county or agency representative with each UAS team conducting surveys to answer questions from citizens. Having a social worker or country representative is also helpful to diffuse any public anger over lack of responsiveness; people in the middle of a disaster do not like to be told to call a 1-800 number, even if their concerns are not life-threatening.

In general, wearing vests and identification (ID) tags and driving in an agency vehicle diffuse fears of privacy violations, and the public is generally supportive of seeing their state or local government use technology for a disaster.

Expect to send out experts with the UAS team for time-sensitive missions during the initial portion of the response phase. Preprogrammed mapping flights may not get the right viewpoints for structural inspection, investigation of the causes of flooding, or overwatch types of missions; real-time streaming may not work. Thus, the UAS team may not get the right information or have a way to get the right information to the right person.

An expert can look at real-time footage and direct the flight; then, call on a radio or cell phone with any immediate findings.

Have a UAS expert work directly with the Air Operations Branch. This simplifies airspace coordination. Route requests through a centralized incident command system where the air branch can assign tasks to manned or unmanned assets (e.g., some missions could be better executed by the Civil Air Patrol than a UAS). This centralization also helps identify opportunities to share data.

Have a dedicated data management policy and manager. The geographic information system (GIS) team won’t be able to handle the additional workload and high-resolution imagery from a single 20-minute flight that can run around 2 gigabytes (GB), so prepare for both data storage (get a hard drive) and the extra manpower.

Any deployment should have a data management policy that specifies ownership of the data (i.e., if a volunteer is flying, all data belongs to the agency and cannot be released without the agency’s permission). The policy should also specify chain of custody procedures.

Don’t expect UAS to reduce manpower; they may actually increase the number of people working in a response, but they should provide capabilities that were not possible or economical any other way. It is likely to be a better use of experts’ time to have a UAS team work for them, rather than expect an expert to fly the UAS, plus take care of charging, keeping up with regulations and airspace, etc.

If you want a single image of a neighborhood or the terrain surrounding a structure or road, consider options such as Hangar 360 or DJI Panorama rather than a preprogrammed flight over the area, then having to upload the data to a post-processing site, etc. These applications automatically rotate the UAS in place and take digital images, then construct a 360-degree panorama.

Volunteers may not be adequately prepared for disaster response, in terms of familiarity with regulations, personal safety, or advanced flight skills.

Plan to fly daily to monitor the dynamically changing event. This means considering access, permission, and manpower availability.

Prioritize vulnerable locations. It may take 2 to 4 hours to reach a location, so there won’t be time to map an entire county with a small UAS during the immediate response phase (even if there are suitable landing zones).

Don’t expect to use UAS for homeowner property damage (e.g., measuring the waterline on a home). Many homes are in neighborhoods with trees that block the view or it is difficult for the UAS to get an elevation view of the house. Consider using a vehicle- or boat-mounted mapping system such as GroundVu instead.

CONCLUSIONS

Small rotorcraft unmanned aerial systems have become increasingly common before, during, and after flooding disasters. A commonly used platform that retails for approximately $1,000 can perform six of the seven basic missions for flood events.

The low cost of current UAS combined with the best practices that have emerged since their first introduction in 2005 with Hurricane Katrina offer a solid foundation for rapid adoption by agencies.

REFERENCES

De Cubber, G., H. Balta, D. Doroftei, and Y. Baudoin. 2014. UAS Deployment and Data Processing during the Balkans Flooding. 2014 IEEE International Symposium on Safety, Security, and Rescue Robotics, October 27–30, Hokkaido, Japan.

Dai, E., A. Venkitasubramony, A. Gasiewski, M. Stachura, and J. Elston. 2018. High Spatial Soil Moisture Mapping Using Small Unmanned Aerial System. *IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium,* July 22–27, Valencia, Spain, pp. 6496–99.

Fernandes, O., R. Murphy, J. Adams, and D. Merrick. 2018. Quantitative Data Analysis: CRASAR Small Unmanned Aerial Systems at Hurricane Harvey. *2018 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR),* August 6–8, Philadelphia, PA, pp. 1–6.

Gornea, D., D. Popescu, and L. Ichim. 2016. Remote Assessment of Flooded Areas Based on Inter-Spectral Statistical Features. *2016 39th International Conference on Telecommunications and Signal Processing (TSP),* June 27–29, Vienna, Austria pp. 707–10.

Mardiatno, D., N. Khakim, and T. K. Priyambodo. 2015. Identification of Flood-Prone Area Using Remotely Sensed Data - Case in Tanjung Selor City, North Kalimantan. *2015 IEEE International Conference on Aerospace Electronics and Remote Sensing Technology (ICARES),* December 3–5, Bali, Indonesia.

Murphy, R. R. 2014. *Disaster Robotics.* MIT Press, Cambridge, MA.

———. 2016. Emergency Informatics: Using Computing to Improve Disaster Management. *Computer*, Vol. 49, No. 5, pp. 19–27

Murphy, R. R., B. A. Duncan, T. Collins, J. Kendrick, P. Lohman, T. Palmer, and F. Sanborn. 2015. Use of a Small Unmanned Aerial System for the SR-530 Mudslide Incident near Oso, Washington. *Journal of Field Robotics*, Vol. 33, No. 4, pp. 476–488.

Murphy, R., J. Dufek, T. Sarmiento, G. Wilde, X. Xiao, J. Braun, L. Mullen, R. Smith, S. Allred, J. Adams, A. Wright, and J. Gingrich. 2016. Two Case Studies and Gaps Analysis of Flood Assessment for Emergency Management with Small Unmanned Aerial Systems. *2016 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, October 23–27, Lausanne, Switzerland, pp. 54–61.

Özcan, O. and S. S. Akay. 2018. Modeling Morphodynamic Processes in Meandering Rivers with UAV-Based Measurements. IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium, July 26, Valencia, Spain.

Rahnemoonfar, M., R. Murphy, M. V. Miquel, D. Dobbs, and A. Adams. 2018. Flooded Area Detection from UAV Images Based on Densely Connected Recurrent Neural Networks. *IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium*, July 24, Valencia, Spain, pp. 1788–91.

Restás, Á. and Z. Dudás. 2013. Some Aspect of Human Features of the Use of Unmanned Aerial Systems in a Disaster-Specific Division. *2013 International Conference on Unmanned Aircraft Systems (ICUAS)*, May 28–31, 2013, Atlanta, GA, pp. 1030–36.

Srivaree-Ratana, P. 2012. Lessons Learned from the Great Thailand Flood 2011: How a UAV Helped Scientists with Emergency Response and Disaster Aversion. AUVSI Unmanned Systems North America 2012, August 6–9, Denver, Colorado.

ONLINE RESOURCES

Center for Robot-Assisted Search and Rescue (CRASAR). http://crasar.org/.

Federal Aviation Administration (FAA) Unmanned Aircraft Systems (UAS). https://www.faa.gov/uas/.

Federal Highway Administration (FHWA) Unmanned Aerial Systems (UAS). https://www.fhwa.dot.gov/uas/.

FHWA Center for Accelerating Innovation Every Day Counts-5 (EDC-5): Unmanned Aerial Systems (UAS). https://www.fhwa.dot.gov/innovation/everydaycounts/edc_5/uas.cfm.

References:

Cheyne, D., Merrill, B., & Boggs, J. (2019). *Use of small unmanned aerial systems for bridge inspection* (FHWA-HIF-19-056) [Tech Brief]. Federal Highway Administration, U.S. Department of Transportation. https://www.fhwa.dot.gov/uas/resources/hif19056.pdf

Rogers, P. (2019). Use of small unmanned aerial systems for construction inspection (FHWA-HIF-19-096) [Tech Brief]. Federal Highway Administration, U.S. Department of Transportation. https://www.fhwa.dot.gov/uas/resources/hif19096.pdf

Murphy, R. R. (2019). *Use of small unmanned aerial systems for emergency management of flooding* (FHWA-HIF-19-019) [Tech Brief]. Federal Highway Administration, U.S. Department of Transportation. https://www.fhwa.dot.gov/uas/resources/hif19019.pdf

Wheeler, P. (2019). *Use of small unmanned aerial systems for land surveying* (FHWA-HIF-20-034) [Tech Brief]. Federal Highway Administration, U.S. Department of Transportation. https://www.fhwa.dot.gov/uas/resources/hif20034.pdf

Federal Highway Administration (2023). *Use of small unmanned aircraft systems for construction quantity estimation* (FHWA-HIF-23-058) [Tech Brief]. U.S. Department of Transportation. https://www.fhwa.dot.gov/uas/resources/hif23058.pdf

Federal Highway Administration (2023). *Use of small unmanned aircraft systems for roadside asset management* (FHWA-HIF-23-065) [Tech Brief]. U.S. Department of Transportation. https://www.fhwa.dot.gov/uas/resources/hif23065.pdf

Federal Highway Administration (2023). *Use of small unmanned aircraft – basic fundamentals* (FHWA-HIF-23-056) [Tech Brief]. U.S. Department of Transportation. https://www.fhwa.dot.gov/uas/resources/hif23056.pdf

Federal Highway Administration (2023). *Use of small unmanned aerial systems for retaining wall inspections* (FHWA-HIF-23-057) [Tech Brief]. U.S. Department of Transportation. https://www.fhwa.dot.gov/uas/resources/hif23057.pdf

Rydlund, P. H. Jr., & Densmore, B. K. (2012). *Methods of practice and guidelines for using survey-grade global navigation satellite systems (GNSS) to establish vertical datum in the United States Geological Survey* (USGS Techniques and Methods 11–D1). U.S. Geological Survey. https://doi.org/10.3133/tm11D1