Drone-Based 3-D Photogrammetry in Building Enclosure Consulting Practice

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THE USE OF drones by building enclosure consulting firms is becoming more common as consultants learn that drones can save time and resources and reduce risk during building assessment. Drone-based three-dimensional (3-D) photogrammetry takes this further by combining drone technology with photogrammetry to create highly detailed, 3-D photomesh models that can be used to document existing conditions, communicate these conditions with project teams, and develop highly defined construction documents faster and safer than previously possible.

WHAT IS DRONE-BASED PHOTOGRAMMETRY (PG)?

"Photogrammetry is the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of recorded radiant electromagnetic energy and other phenomena."[1]

Drone-based PG utilizes a drone as the primary method for capturing images and data to develop PG datasets and models.

HOW DOES PG PROCESSING SOFTWARE WORK?

One of the keys to understanding the PG process and achieving desired outcomes is having a basic understanding of how PG software uses two-dimensional (2-D) images to create a 3-D photomesh.

Generally, most PG software utilizes three steps to create a 3-D photomesh.

- Input: All captured photographs are input into the software. It is important to note that it is often not possible to add or delete photos from the overall photoset once the process has begun.
- Determining tie points: The software then processes the complete photoset, looking for common points (tie points) between the photos. A general rule is that each tie point should be included in a minimum of three separate photos, which often requires a minimum of a 70% end/front lap and 70% sidelap between each photo.
- Creating a photomesh: The software then analyzes processed photographs to extract 3-D information and develops the photomesh. Typical 3-D information includes distance, area, and elevation of the known tie points, camera focal length, global positioning system information, and more.

BENEFITS TO USING PG

Drone-based PG can provide very detailed, 3-D imagery of exposed building facades and components. Depending on the desired deliverable, PG can significantly reduce or sometimes eliminate physical assessment of difficult conditions, thereby reducing assessor risk and cost.

Three-dimensional photomesh models can often be shared with clients and team members, allowing all users to have the same project perspective and access to imagery data. A photomesh can be a powerful tool to convey relevant data during meetings and presentations.

PG is also used to provide base information for drawings and other deliverables. This is particularly effective for structures with little or no as-built information and for structures that have had undocumented repairs or alterations. PG is well suited for documenting existing conditions to provide a benchmark for future comparison analysis. Scaled photomeshes can also be exported into building information modeling (BIM) and other computer-aided design (CAD) software systems to serve as the basis for very detailed drawings.

Drones and PG software can also be used to develop 2-D orthomosaics. These "homemade Google Earth" images can be used to develop accurate, scalable roof and site plans.

DRAWBACKS AND WHERE DRONE-BASED PG MAY NOT WORK WELL

Drone-based PG is only as good as what the drone camera can see. Buildings or surfaces that are obscured by trees, landscaping, or anything else that gets between the drone and surface will be a problem. Trees, power lines, and other obstacles can also present crashing hazards.

Highly reflective surfaces, such as glass, polished surfaces, or water, and very uniform surfaces, such as monolithic surfaces with few penetrations or large fields of exterior insulation and finish systems, can be problematic for PG software to process.

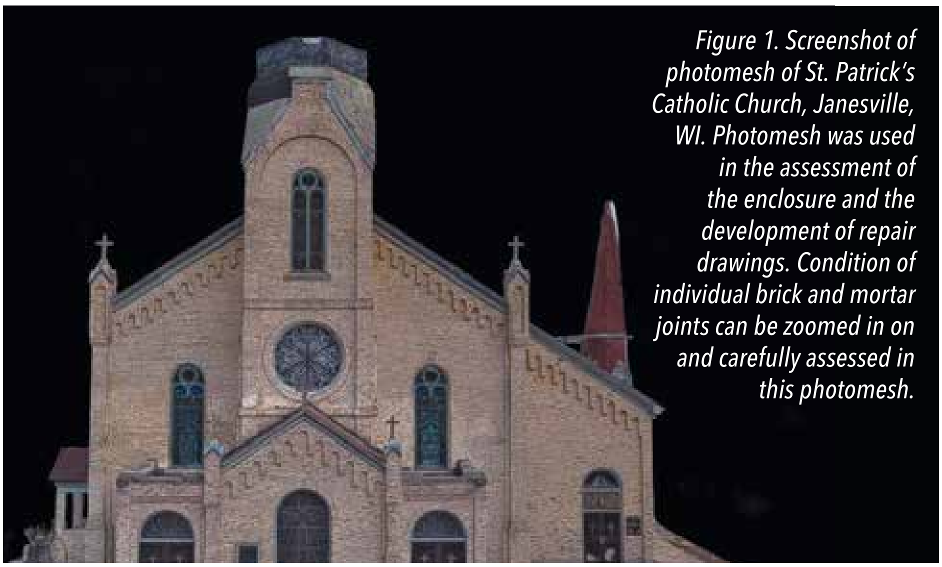

Figure 1. Screenshot of photomesh of St. Patrick's Catholic Church, Janesville, WI. Photomesh was used in the assessment of the enclosure and the development of repair drawings. Condition of individual brick and mortar joints can be zoomed in on and carefully assessed in this photomesh.

Drone-based activities are also highly regulated by the Federal Aviation Administration (FAA), local municipalities, and building owners. To ensure the safety of the airspace, most flights are expected to be filed with the FAA using the Low Altitude Authorization and Notification Capability (LAANC) program. Through the LAANC program, operators can obtain permission to fly many buildings within controlled airspace with certain restrictions.

However, requests for some buildings located within close proximity to airports, designated no-fly zones (NFZs), or other restricted areas may not be granted. Since beginning our drone program, we have used a drone in over 15 states and have had two requests denied (both located near airports). A drone would have benefited a project located within the Washington, DC, NFZ, but we did not attempt to get permission.

Consultants should also be aware that drones can make bystanders very angry, even when being operated within all legal bounds. There are well-documented examples of the remote pilot in command being physically threatened and assaulted and having their drones shot at or shot down (and not just in the US).

PG requires significant computer processing and data storage. For example, a large building model with very low ground sampling distance (GSD)/high definition may take three to four days of continuous processing time using a dedicated workstation. Photo storage and resulting photomeshes can also use consume hundreds of gigabytes. In less than one year, our drone-related file storage consumed over 5 terabytes.

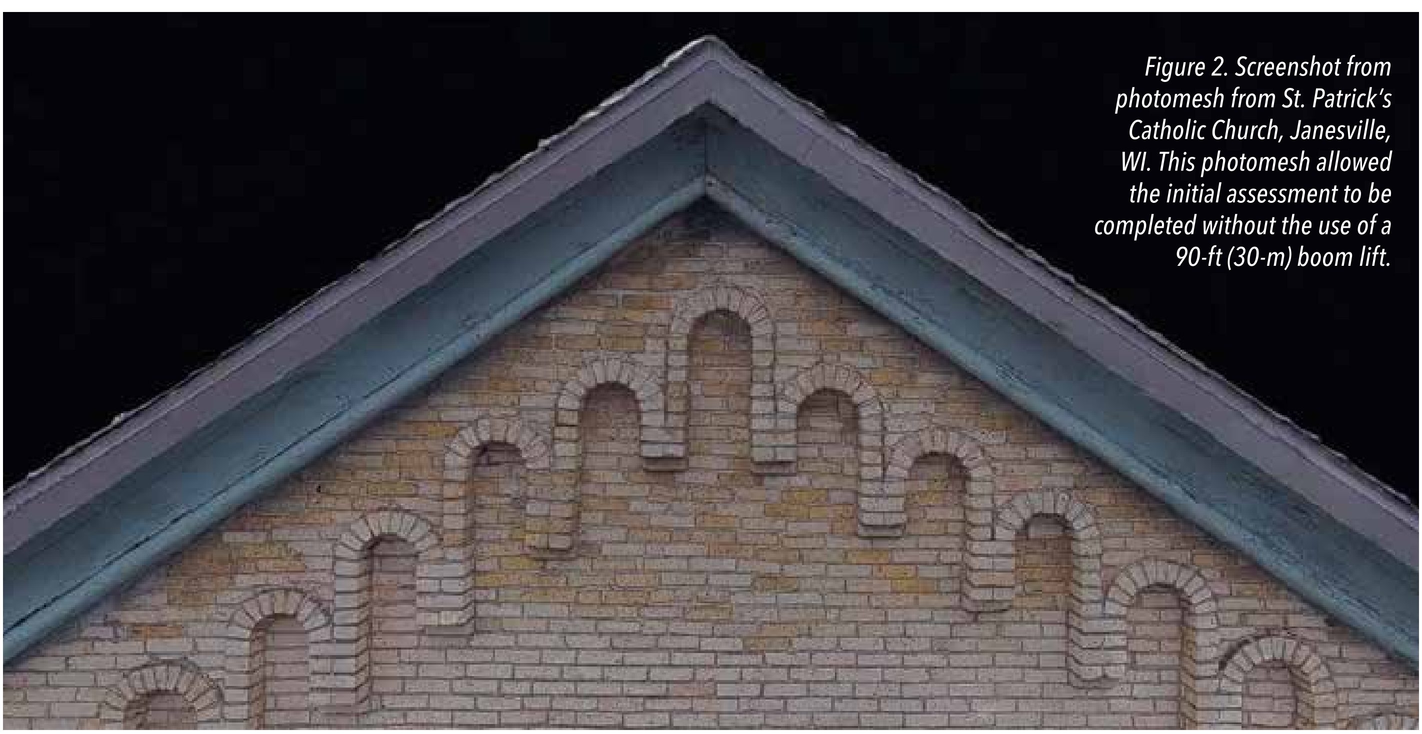

Figure 2. Screenshot from photomesh from St. Patrick's Catholic Church, Janesville, WI. This photomesh allowed the initial assessment to be completed without the use of a 90-ft (30-m) boom lift.

Drone operations can also be impacted by birds and other animals. In our experience, geese and seagulls are the most problematic, particularly during their nesting and posthatching periods, as they will attack drones in defense of their nests. While we have not had problems with hawks and other raptors, there are documented instances of drones being attacked by these birds. We have also noticed that drones irritate dogs, resulting in barking and aggressive behavior.

Weather and ambient conditions are critical considerations in drone operations.

- Wind: While most drones can operate in winds approaching 20 to 25 miles per hour (32.1-40.2 kilometers per hour), flying in high winds reduces camera stability, makes flight erratic, and consumes more battery during flight. As a general rule of thumb, if it is too windy to roof, it is too windy to fly. Wind often swirls around buildings and can easily overwhelm a drone. Wind speeds are typically greater at higher flight altitudes.
- Precipitation: While a handful of drone models can operate during some precipitation, taking high-quality imagery is the goal of each flight. Drone imagery collected during precipitation will be significantly degraded.
- Lighting: Completely overcast days are the best. On sunny days, flight planning should consider the angle and direction of the sun to reduce shadows and uneven lighting conditions.
- Temperature: Drones and their batteries are temperamental and operate best in specific temperature ranges. Another rule of thumb: If it is too hot or too cold for the operator, it is too hot or cold for the drone.
  - Cold weather: We have flown in temperatures as low as 15°F (-9°C) utilizing an insulated warming box to keep batteries warm. Cold weather also cools batteries faster after flight. We have experienced some minor remote control operating issues during cold weather.
  - Hot weather, high humidity: Drone performance can be degraded during very hot, humid conditions, resulting in increased battery depletion. Drones and controllers can also overheat during flight, although in our experience drones get hotter when on the ground during battery changes than they do while in the air, when their propellers are helping to cool them. Drone batteries also need increased cooling periods in hot weather before recharging. Many operators will cool their batteries between flights with coolers or air-conditioned vehicles to speed the cooling process.

Figure 3. Screenshot of photomesh of St. Patrick's Catholic Church, Janesville, WI.

DRONE-BASED DATA COLLECTION METHODS

The two general methods can be categorized as either stand-off or close-up. These two methods are often determined by available drone equipment, building or subject to be scanned, and the desired outcome of the photomesh.

STAND-OFF METHOD

Drone-based PG generally began using high-end drones with very good cameras to capture imagery to develop surveys, mapping, material volume studies, and other deliverables for large areas of land. Quadcopters, hexcopters, or even fixed-wing aircraft with very high-end cameras, infrared, and light detection and ranging (LIDAR) sensors are used to collect imagery from distances several hundred feet away from the subject. The resulting PG utilizes fewer, very high-quality photographs to create photomeshes. GSD results for this method and type of surveying are often measured in centimeters.

CLOSE-UP METHOD

We utilize the close-up method for building assessment. This method often uses smaller, less expensive drones with good cameras. Quadcopters are commonly used to collect imagery, often within 8 to 20 ft (2.4 to 6 m) of the subject. Infrared sensors can also be used to collect data for PG. This method utilizes higher numbers (often thousands) of high-quality photos to create photomeshes. GSD results for this method are often 1 to 2 mm.

HARDWARE RECOMMENDATIONS

Hardware could easily be the topic of a stand-alone article. Following are a few considerations:

- What will be the drone's primary use? Stand-off or close-up applications? Will it be used in structure assessment, photography, or cinematography applications? Will it be used to collect infrared imagery? We prefer utilizing different drones for multiple purposes to maximize the benefits of each drone instead of relying on one drone for all tasks.
- Where will the drone be used? Some drones utilize geofencing around schools, restricted areas, and other areas defined by the manufacturer. Geofences restrict the drone's ability to fly within their bounds. Geofences can often be disabled with the proper planning and authorization, but this is not always successful, which can be costly and embarrassing when trying to complete a time-sensitive mission with onlookers waiting to watch the drone in action.
- What kinds of clients will the drone be used for? The US government and many municipalities require the use of drone manufacturers from the current Blue Unmanned Aerial System (UAS) list. Blue UAS manufacturers have been vetted by the US government for national-security-, data-security-, and supply-chain-security-related concerns. It is important to note that the world's leading and most popular drone manufacturer is based in China and will likely never be approved.

- Batteries: We recommend purchasing enough batteries to sustain five to six hours of near-continuous flight. The alternative would be having enough batteries, battery chargers, and a power source to recharge batteries continuously during flight operations. We currently have enough batteries for our primary assessment drone for three hours of continuous flight, three battery chargers, a small gasoline-powered inverter generator, a small solar generator (used as a high-capacity battery), a few deep-cycle lead-acid batteries, and a small 500-watt inverter to provide options for powering rechargers and our battery-warming box.
- Backup drones. Drones will crash, particularly when utilizing the close-up collection method. We have experienced crashes because of the drone flying into very small, bare tree branches during autonomous flight and battery or mechanical failure. Having a backup drone is good insurance to keep flight operations moving while waiting for repair or replacement, which can take weeks.

PROJECT WORKFLOWS AND POSTPROCESSING

Depending on the deliverable required, our general workflow is as follows:

1. Initial meeting to determine project requirements, desired outcomes, deliverables, required GSD (the distance between two consecutive pixel centers measured on the ground), etc.
2. Preproject flight and logistics planning:
   a. This includes review of the project location, FAA clearance/LAANC applications, and administrative submissions and requests.
   b. Flight planning
      i. Plan individual missions to account for overall project size, required battery changes, maintain overlap between missions.
      ii. Visual Line of Sight/Beyond Visual Line of Sight (BVLOS) considerations. Note: BVLOS must have an FAA Part 107 waiver, which is difficult to obtain.
      iii. Determine if/how many visual observers are required.
3. GCP coordination: Determine best locations for GCP to help coordinate missions, integrate LIDAR if being used, and introduce a known-dimension object to define photomesh scale.
4. Internal resource planning: Resource planning includes personnel, equipment, and computer resources. Complete-building or large-elevation photomesh processing often takes days to complete for a single project.
5. Field operations, including drone flights and LIDAR data collection.
6. Data download and backups.
7. Initial photo processing and photomesh creation.
8. Publish/share model for review, client/team use.
9. Conversion of photomesh to point-cloud when combining PG and LIDAR.
10. Importing photomesh or pointcloud to BIM.
11. BIM processing.
12. Drawing and document development.

Not all these steps are completed for each project. Some of these steps are completed concurrently or in different order, depending on the project and desired deliverable.

COMPUTER AND SOFTWARE RECOMMENDATIONS

In our opinion, computers used to process PG are like trucks, shoes, money, etc.: You can't have too much computer. Similarly, PG deliverables are often very large, making high-speed internet, both upload and download, very important. Keep in mind that software manufacturer hardware requirements are the bare minimum.

Our processing computer is incredibly powerful. This machine performs well, but more storage space would be useful. Here are its basic specifications as of 2022:

- Asus Prime Z590-A motherboard, 128 GB DDR4 RAM maximum
- Intel Core i9 10-core, 3.70 GHz processor
- CPU cooler
- 2 TB solid-state drive
- 6 TB internal SATA hard drive internal
- EVGA GeForce RTX 3070 Ti XC3 Ultra Gaming graphics card with 8 GB GDDR6X RAM and iCX3 cooling
- Intel Ethernet Converged Network Adapter X550-T2
- Windows 10 Pro 64 OEM supporting up to 512 GB RAM

There are multiple PG software programs. We have basic familiarity with a few and selected a very robust solution based on our needs. In our experience, there are no free or very low-cost options that meet our needs. Our selected software can process large photomeshes, export

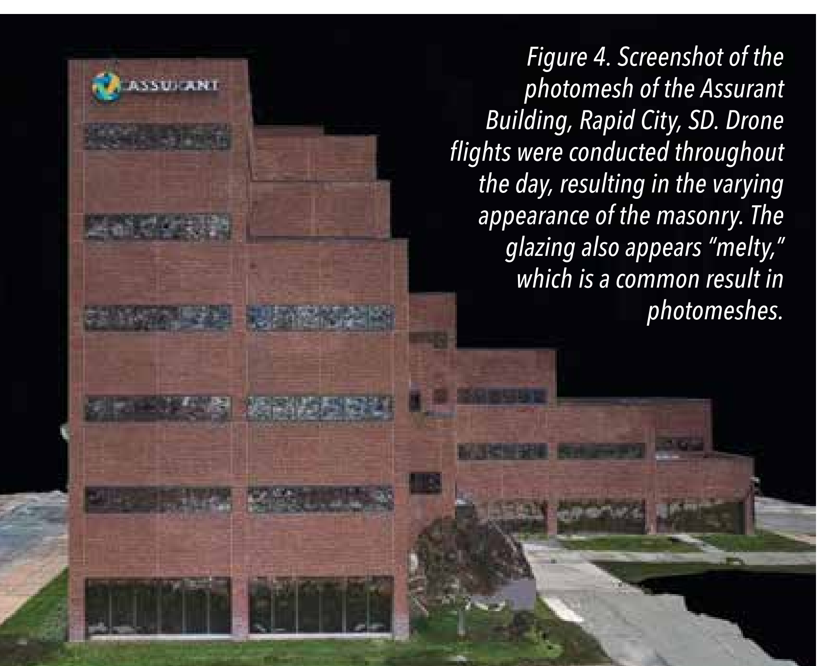

Figure 4. Screenshot of the photomesh of the Assurant Building, Rapid City, SD. Drone flights were conducted throughout the day, resulting in the varying appearance of the masonry. The glazing also appears "melty," which is a common result in photomeshes.

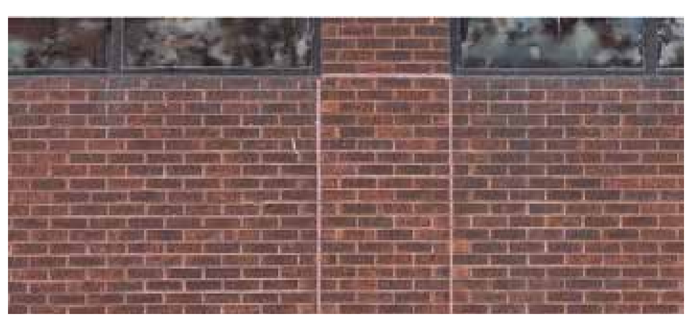

Figure 5. Screenshot of the photomesh of the Assurant Building, Rapid City, SD. The masonry control joint sealant condition is clearly visible. This level of definition would have otherwise required a 120-ft (40-m) boom lift to access this location. Note "melty" appearance of the glazing.

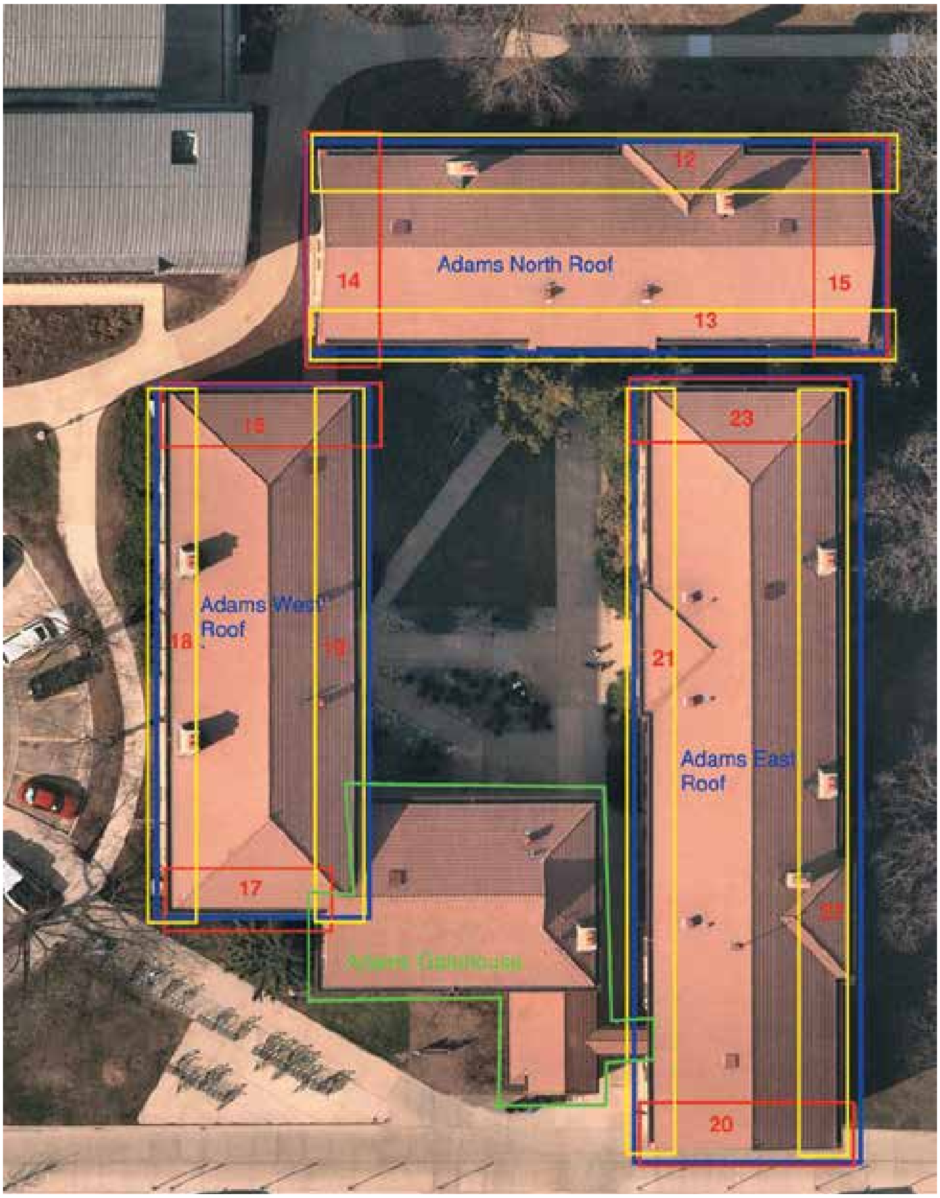

Figure 6. Image of flight plan outlining individual, overlapping missions to complete acquisition of the complete building. Trees and pedestrians were quite challenging on this project, resulting in a few missions not being flown.


Figure 7. Screenshot of photomesh used to assess stone cladding. Photomesh was used in conjunction with manual assessment, removals, and lab testing. Photomesh was also used to develop drawings labeling each individual stone on the building.

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meshes into several different format types, convert photomeshes to point clouds, combine point clouds with photomeshes, and more. For an additional fee, this software solution also has the capability to upload our data to the cloud and process very large projects on the software manufacturer's servers, freeing up our internal resources.

Sharing our models with clients and team members was initially challenging. While our software has a "free" viewer and cloud access that can be shared externally, it is very cumbersome and difficult to use. External users do not want to download apps, sign up for software access, set passwords, and then navigate through multiple pages to get to a model. We found a third-party, cloud-based application to share models. Although not cheap, this application is easy to use, easy to access, and has simple model manipulation and measurement tools. Perhaps more importantly, this application stores models on its own servers and uses partial file management to allow viewing on most devices with a good internet connection.

We have found the best way to postprocess photomeshes is by importing them into a BIM platform. Once the model is in BIM, it can be manipulated and processed using BIM tools to create scaled drawings. We primarily utilize 2-D CAD in our practice, which requires us to create 2-D elevations in BIM and export them to CAD.

Unfortunately, if highly detailed line drawings (i.e., noting individual stone, brick, exact crack locations, etc.) developed from photomeshes are required, "tracing" these details in BIM is still necessary. Software to assist with processing the incredible amounts of data to develop very detailed drawings in BIM does exist, but in our experience the "holy grail" that completely processes all the resulting detail into exact line drawings has yet to be found.

PHOTOMESH AND POINT CLOUD INTEGRATION

Along with many other firms, we have begun to integrate photomeshes with point clouds obtained by LIDAR. In our experience, this integration utilizes strengths of each method to develop a more thorough and detailed final product.

In addition to the use of a drone, LIDAR is used to capture data from ground-based locations that would be difficult to access. LIDAR point clouds also assist with defining overall accuracy of the resulting model. Finally, and perhaps more importantly, LIDAR can be used underneath overhangs, under trees, and inside structures where drone operation would be impossible. This combination also allows creation of entire-building BIM models that include interior and exterior surfaces.

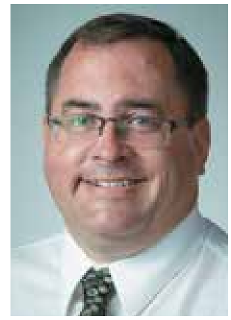
CONCLUSION

Drone-based photogrammetry provides a tremendous tool for consultants and designers to thoroughly document existing conditions, share resulting information with external team members, and develop highly detailed and accurate reports and drawings, all while reducing risk and exposure to potentially unsafe conditions.

REFERENCE

1. James S. Aber, Irene Marzolff, and Johannes B. Ries. 2010. *Small-Format Aerial Photography*. Elsevier, ISBN 9780444532602.

ABOUT THE AUTHORS



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Jenn Boelter *was the director of virtual modeling and chief pilot for Building Envelope Professionals Group LLC (BEPG). Boelter provided oversight and management of the BEPG drone program. Boelter routinely conducted 3-D photogrammetry data acquisition and modeling and continues to lead BEPG's "drone to BIM" workflow development. She also provided laser scanning, point cloud development, and the integration of laser scanning and photogrammetry 3-D meshes.*

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