ND in 3D: Structure from Motion

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Introduction

Detailed terrain models are the best way to visualize and measure the ground surface. High-quality digital elevation models (DEMs) were formerly only produced from airplane-based laser instruments like LiDAR, but now these can be created using a simple drone-mounted camera. The process of making measurements from photographs is called photogrammetry. Put simply: when a camera moves, objects in the photos move varying amounts relative to their distance from the camera. When the same point on the ground is captured multiple times from different angles, software can interpret those geometries and generate a 3D model. This type of photogrammetric technique using 2D photos from a moving camera to generate 3D landform models is called Structure from Motion (SfM).

Data Collection

The North Dakota Geological Survey (NDGS) has been utilizing UAS (unmanned aerial systems) technology since the spring of 2017 and has acquired over 17,000 images from 89 projects (Maike, 2018). All these photos were attained using DJI's Phantom 4 Pro drone (Fig. 1). This popular model is relatively easy to operate, affordable, and acquires spectacular imagery. It has a 20-megapixel camera, 1080p video quality, and up to 25 minutes of flight time per battery. The drone can be manually flown to acquire various imagery; however, the NDGS has increasingly been using software to fly automated, gridded surveys.

In 2019, the NDGS began using automated UAS flight software called Maps Made Easy. This is an inexpensive, app-based program that allows geologists to create orthophoto maps of stitched and geometrically corrected aerial photographs and construct a 3D surface model using autonomous planned flights. These automated flights still require that a FAA Part 107 certified pilot have the controls in their hands if any mishaps were to occur. By pre-programming the route, altitude, speed, and photo interval, flights are efficient, repeatable, and capable of capturing up to 300 photos per battery. Figure 2 displays a screenshot of the software being used on an iPad. The software conveniently allows for the flight planning to take place in the office before heading out into the field. The white lines in the center of the screenshot are the path the drone will navigate to take 250 images of the 10.3-acre site. The grid direction can be adjusted as needed. In this case it was selected to avoid extended flying time over the highway. The photos are taken as a plan view (horizontal plane) in relatively flat terrain but can also include oblique photos to better capture vertical faces of complex landforms. The flight speed of the drone is automatically calculated based on the amount of blur in the photographs.

Figure 1. The NDGS's Phantom 4 Pro.

Figure 2. iPad screenshot of Maps Made Easy software. Site location: Morton County, North Dakota.

If the drone is flying at a low altitude or a longer shutter speed is required for dark conditions, the drone will slow to maintain sharp imagery. The app also provides estimates for the duration of the flight and size of the photo set.

There needs to be an adequate amount of overlap between photos to provide the multiple perspectives required for photogrammetric techniques to bring the photos into three-dimensions. A minimum of 60% overlap is recommended, however, the NDGS typically acquires imagery with 75-80% overlap. Maps Made Easy allows the import of Shuttle Radar Topography Mission elevation data, which enables the topographic relief in the area to be applied to the drone flight. Users can program the drone to stay at a designated height above Earth's surface. This allows software to more easily stitch together imagery in large datasets and allows for a more seamless collection of data in areas with high relief. The drone elevation (blue line) and earth elevation (red) can be seen in the cross-section in Figure 2. The mission shown was flown to acquire imagery of a landslide impacting ND Highway 49 south of Glen Ullin.

In addition to using automated flight technology, users place ground control points within survey areas to attain more precise mapping (Fig. 3). This allows users to make repeat trips to survey sites to detect features such as landslide movement, volumetric change, and plant health analysis. These ground control points or targets are placed throughout the survey area and are easily recognizable. A user would place the targets, collect a GPS measurement at each location, and then conduct the drone survey. Following the collection of the data, the imagery will be post-processed in software. In our case, the NDGS uses a program called Agisoft. During post-processing, the targets can be identified and assigned the GPS points that were collected in the field. The advantage of using ground control points is to have a more accurately positioned ground surface versus using only the GPS points collected by the drone in the air.

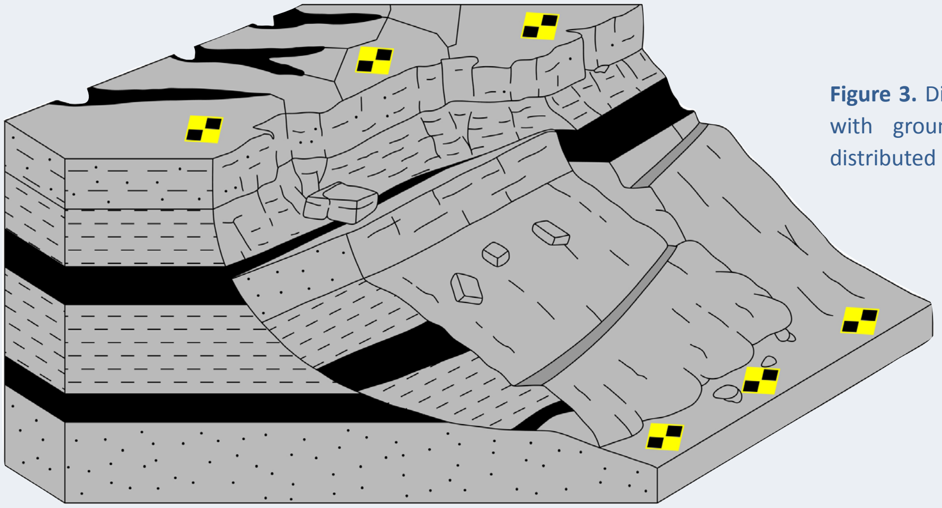

Figure 3. Diagram of a rotational slump with ground control points (boxes) distributed around the area of interest.

Processing

Field collection of data is the comparatively simple part of generating three-dimensional models. Software and computing power do the heavy lifting to generate SfM products from hundreds or thousands of photos. There are several popular software programs that use photogrammetric techniques to generate 3D models, such as Pix4D, DroneMapper, Agisoft, DroneDeploy, and PrecisionHawk 3D. The NDGS used trials of several of these before choosing Agisoft and has been very impressed with its user-friendly interface and variety of features including photogrammetric triangulation, digital surface model generation, georeferenced orthomosaic export, 3D model generation and texturing, and panorama stitching. A simple example of the software's applicability is a location adjacent to ND Highway 49, south of Glen Ullin, North Dakota. This site has a well-defined landslide that has impacted the highway (Fig. 4). The NDGS collected 99 airborne pictures from the 17-acre site which were then used to create a 3D-model, orthomosaic, and a digital surface model (Figs. 5 and 6).

Can the typical home computer process this amount of data? The simple answer is "no," but many offices may already have a GIS computer up to the task of compiling small to medium-sized projects. The NDGS runs Agisoft on its GIS workstation (Xeon Gold 6144 [3.5GHz, 4.2 GHz Turbo, 24.75MB Cache] processor, NVIDIA Quadro P4000 8GB graphics card, 64GB [4x16GB] DDR4 RAM, 2TB Class 40 Solid State Drive, and two additional 3.5" 4TB 5400rpm SATA hard drives for data storage). These specifications allow the average 500-image dataset to be compiled in an average of 5 hours and the machine to be used for other tasks while it is processing. After a significant amount of research and cost/value analysis we found this computer build to be very robust for the cost. Larger datasets severely bogged down older NDGS workstations running at or near suggested specs (a quad/hexa-core CPU, 32GB RAM, 2GB GPU, and solid-state drive is typically recommended for projects over 500 images), and the operator would not be able to run any additional programs. This new computer has allowed the user to process data and to continue normal day-to-day tasks on

Figure 4. NDGS Geologist and FAA Part 107 Pilot, Chris Maike, examining a landslide impacting ND Highway 49.

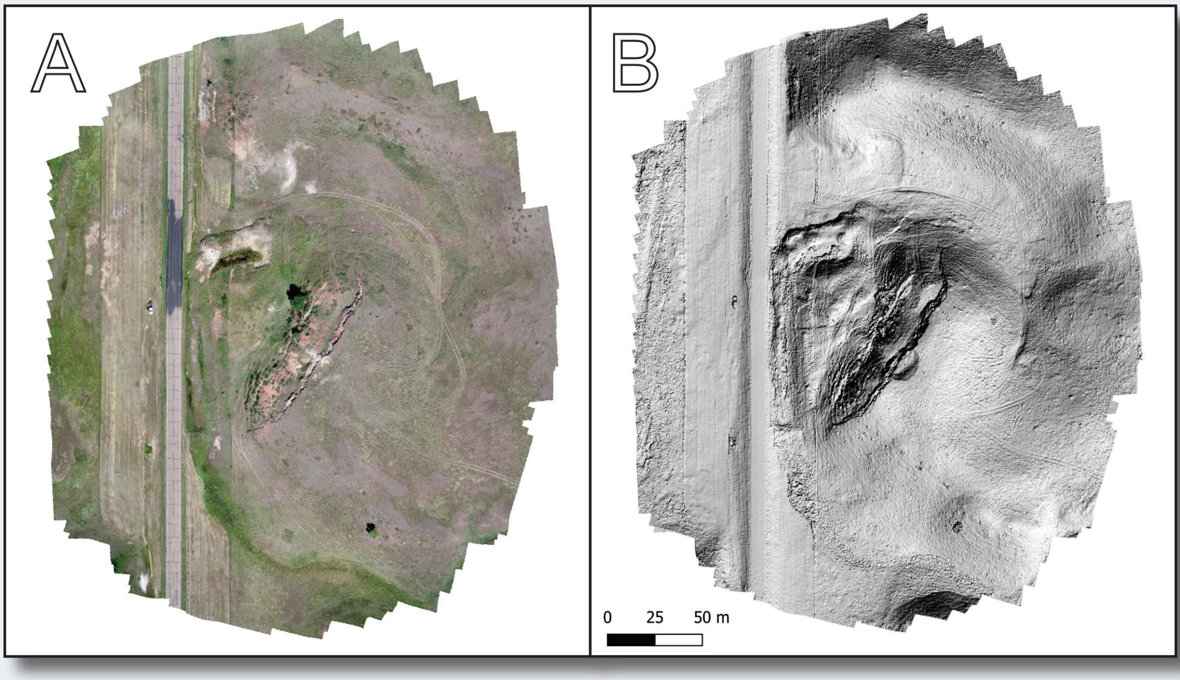

Figure 5. (A) Orthomosaic and (B) digital surface model of a landslide impacting Hwy 49 south of Glen Ullin.

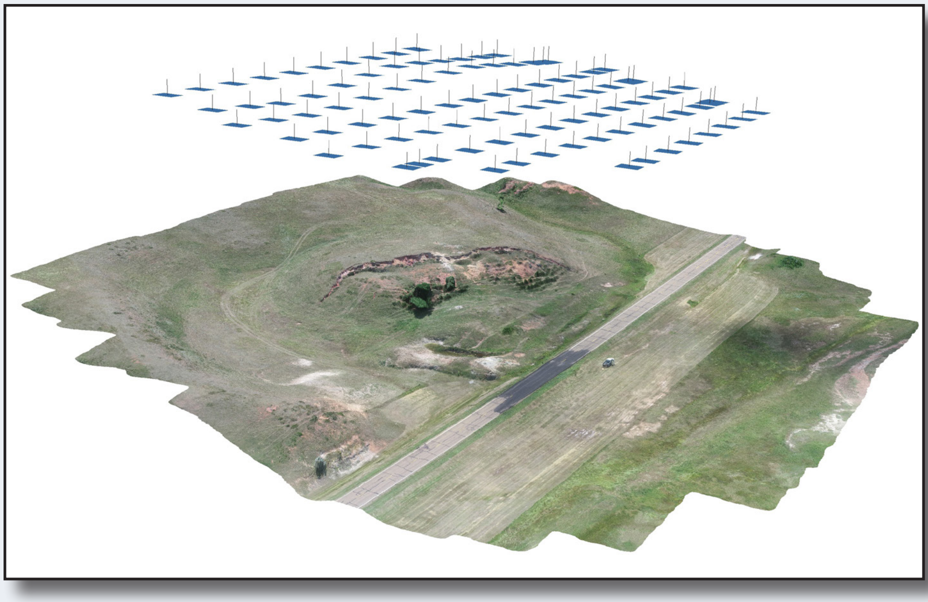

Figure 6. 3D-model of Hwy 49 landslide south of Glen Ullin. The image displayed is an Agisoft screenshot. The tiles in the sky represent the photos collected from the drone used to make the model (below).

the machine as well. For users interested in dedicating a machine for this purpose, the most important component to invest in would be the processor. This is the work horse representing the computational power of the machine.

SfM or LiDAR? Advantages of models produced from different methods

The most obvious advantage of drone-based structure from motion models is that they are capable of unprecedented levels of resolution. A drone flight at 200 feet and 80% overlap can produce a surface model with 3.6 cm resolution. Resolution is inversely related to the drone's height above the ground, so resolution approaching 1 cm is possible for very low drone flights. The latest airplane-based public LiDAR dataset is flown to produce 1-meter resolution DEMs. Figure 7 illustrates the increased clarity offered by these small-scale, low-altitude drone flights versus the statewide LiDAR, which is collected for maximum coverage for use at a larger scale. For sites larger than a square mile, the advantages of a drone SfM resolution diminish, and multiple days may be needed to collect and compile the imagery. For small sites, where capturing detail is paramount (like the tension cracks of a landslide about to fail), every pixel is important.

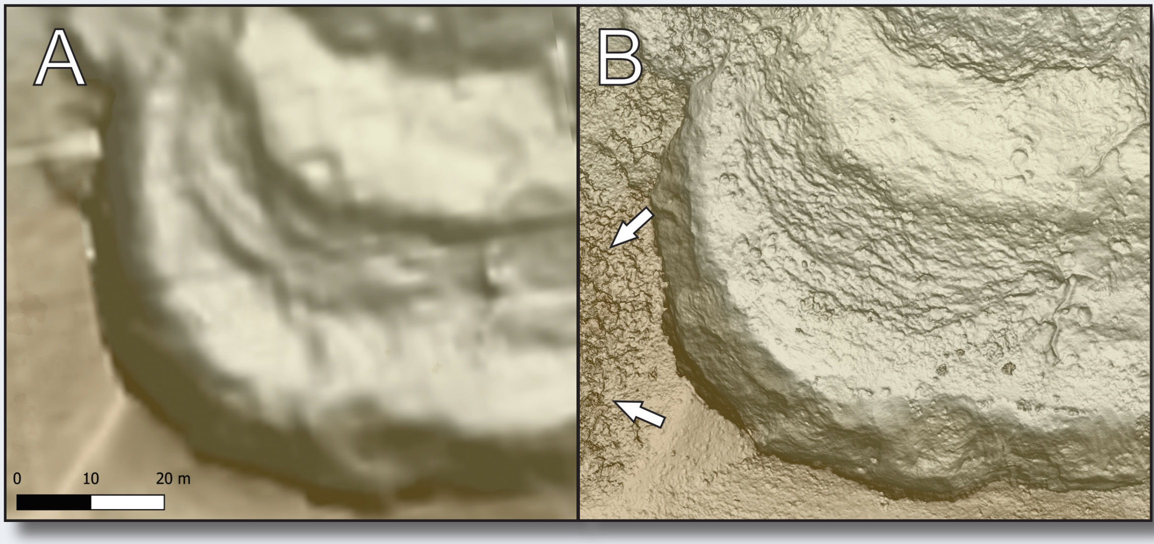

Figure 7. A landslide in northwestern Dunn County viewed as (A) a bare-earth surface model produced from aircraft-mounted LiDAR and (B) an SfM model produced from NDGS drone imagery. Note the advantages of removing heavy tree cover with LiDAR (arrows), but the drone imagery (flown at 200 ft.) offers a marked increase in resolution.

An active instrument like LiDAR emits its own signal and measures the time it takes for the signal to be reflected back to the sensor (Maike, 2016). Passive sensors, such as cameras, collect natural "signal" (light) and do not directly measure distance, and thus photogrammetric methods have certain limitations. One scenario where SfM terrain models show these limitations is in areas of heavy tree cover. To create a bare-earth model from LiDAR, the last portion of the signal reflected back to the sensor (that traveled the farthest distance) is used as the ground elevation value. Earlier signal returns from the tree canopy can be easily filtered. To model the forest floor with SfM software, it would need the same spot photographed from several angles. This is not typically feasible through sporadic bare patches in the canopy, and thus the surface of SfM models will be that of the tops of trees, bushes, and grass where present. Individual trees can be removed in post-processing (and the ground elevation below them inferred), and marginal improvement can be seen in spring (pre-leaf), or fall (post-leaf), but branches still introduce considerable interference.

For identifying change to the surface of North Dakota (measuring erosion, sedimentation, landslides, human earthwork, etc.) multiple elevation datasets are needed to compare and detect change. Most of North Dakota has just one available LiDAR elevation dataset. Although this coverage is considerably better than many states, the prohibitive cost of airplane-based LiDAR means the temporal resolution of public LiDAR datasets may never be high enough for detailed study of active processes. Some of the first re-collects currently underway in the Red River Valley will update LiDAR collected nearly a decade ago. By contrast, drone-based SfM models could easily be collected and processed daily, if needed, for sites where change detection is of high interest. The NDGS has conducted initial flights of several recently active landslides and will continue annual (or more frequent) flights to monitor for slide reactivation or additional failure. The ability to quickly and easily acquire high-resolution spatial and temporal data on demand will allow unprecedented visual and quantitative information on these costly geologic hazards.

Surface models capturing different moments in time need to be directly overlain for quantifiable change detection, so accuracy is highly important. Because the GPS points collected by the drone with each photo contain varying degrees of error, a SfM model needs additional spatial information to correctly place it on the globe. Traditionally, ground control points are collected in the field and the resulting accuracy of the model is on par with the accuracy of the GPS receiver being used. If it is unsafe or unfeasible to collect ground control, models can also be manually georeferenced to an existing accurate dataset, like LiDAR (the latest QL2 LiDAR in North Dakota has approximately 10 cm vertical accuracy). The most accurate methods use real-time kinematic (RTK) drone systems, which utilize a base station to produce survey-grade accuracy. RTK drones are several-fold more expensive; however, and many applications do not require the 5 cm accuracy that these systems are capable of.

An exciting 3D future

The NDGS is finding more and more applications for UAS technology, especially structure from motion, across a variety of projects. On-demand, low-cost, high-resolution geotechnical data will be a critical support mechanism to geoscientists in their mission to quantify and monitor the complex geologic processes acting on the surface of North Dakota. Volumes and rates can now be calculated with unprecedented ease and precision. The applied knowledge gained from UAS data will empower decision makers to more efficiently protect the environment, homes, and energy and transportation infrastructure. As our dataset of these repeat flights expands, so does our understanding of the drivers of change on North Dakota's landscape.

References

Maike, C. A., 2016, LiDAR – What is it and how do we use it? Geo News, v. 43, no. 2, p. 12-13.

Maike, C. A., 2018, LiDAR – Drone Applications at the NDGS: Geo News, v. 45, no. 1, p. 16-17.