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UTILIZING UNMANNED AIRCRAFT SYSTEMS FOR GEOLOGICAL STRUCTURE MAPPING

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ABSTRACT

Unmanned aircraft systems (UAS) are useful in providing overlapping images required to generate three-dimensional point clouds of topography using photogrammetry at a resolution necessary for mapping geologic structure. Elevation in open pit mines changes quickly, so a method of following the topography with flight planning software is required to 1) achieve a constant ground sampling distance, and 2) tilt the camera (sensor) axis perpendicular to local slope surface. Because no commercial software was available to create a flight plan that met these requirements, Call & Nicholas, Inc. developed one.

The following acronyms are used throughout this paper:

Table 1. List of Acronyms.

Unmanned Aircraft Systems	Drone, UAS
Call & Nicholas, Inc.	CNI
Ground Sampling Distance	GSD
Centimeters	cm
Millimeters	mm
Drawing Exchange Format	DXF

INTRODUCTION

Drones are a useful tool for gathering and visualizing geologic data in the mining industry. Additionally, drones offer the ability to capture a large amount of data quickly and in areas where human access may be difficult, such as inaccessible mining benches or areas of slope instability. The state of the art for mapping geologic structures in three dimensions is to use overlapping two-dimensional images to produce three-dimensional point clouds using photogrammetry. Mission planning software programs the drones to collect images at predefined intervals set to the correct overlap needed for photogrammetric processing. Commercially available software can be used to control the drone to take images at defined intervals, but they typically assume relatively flat topography. Within the open pit mine setting, much of the geologic data needed is found on the near vertical bench faces and is not captured from a vertical camera axis. Additionally, open pit topography rapidly changes in elevation and a constant flight elevation will degrade the image quality for the lower elevation areas. CNI has developed a flight planning tool that follows the mined topography and adjusts the drone mounted camera angle to collect images with a constant ground sampling distance over the entire pit slope. The benefits of this method are that (1) the results include geologic structure data on the face of the benches, and (2) the point cloud resolution is consistent throughout the entire scan. DronePlan3D, a custom-built flight planning program, was developed because no software was commercially available to accomplish this task.

BACKGROUND

In early 2018, the feasibility of using drones to collect data for geologic mapping was evaluated by CNI. Many mines that CNI consults for have been purchasing consumer grade drones, such as the DJI Phantom 4 Pro, to take videos of production blasting and to survey stockpiles, but mapping the in-pit highwalls was rarely performed. When the in-pit highwalls were mapped, this was typically done by one of two methods. The first was to use flight planning software created by the drone manufacturers or a third party. The software determines the flight path, number of images needed, flight height, and speed required to obtain images with the correct amount of image overlap needed for photogrammetric processing. Early versions of these pieces of software did not consider changes in topography, and a constant flight elevation was assumed for the entire flight. Using this method yields unsatisfactory results at the toe of the pit where the resolution of the images is significantly lower than at the crest of the pit. This limitation has been fixed recently, as a few software packages, such as UgCS, DJI GS Pro, and Phoenix Flight Planner, now allow for terrain following with custom elevation surfaces. However, this methodology still has a major flaw in that there is a significant blind spot on near vertical faces due to the vertical camera alignment (e.g., bench faces) where most of the geologic structure information is found. Manual adjustments of the camera gimbal can be made to try and capture information on the bench faces, but the change in camera angle can significantly change the effective image overlap percentages. The second method that mine sites use is to manually fly the drone and capture a collection of images in an unorganized fashion. This method allows for the information on the bench faces to be captured, but the actual image overlap percentages are unknown until processing takes place after the flight has been completed. Knowing these two methods would yield unsatisfactory results for consistent and systematic point clouds, CNI sought a more engineered approach to acquiring high resolution point clouds of open pits with the drones that many mine sites already have. A methodology and software package called DronePlan3D was developed by CNI that enables drones to achieve a constant GSD over rapidly changing elevations found in open pits and adjusts the camera axis in order to be perpendicular to the average local slope surface found within the camera sensor's view. The only data required to create these flight plans includes a recent topographic map of the area, and the properties of the camera sensor, specifically the forward and side field of view in degrees. A simple representation of the drone flight paths moving down the slope and viewed in cross section is presented in Figure 1.
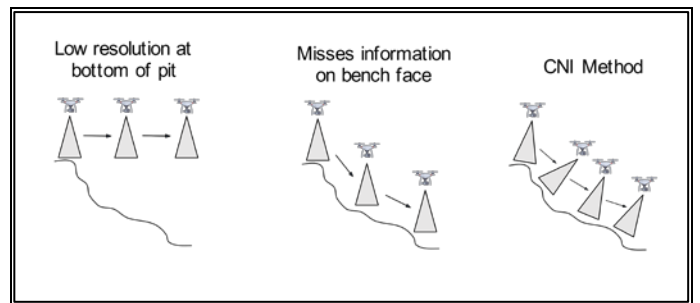

Figure 1. Different methodologies of flight paths moving down a slope and viewed in cross section.

PHOTOGRAMMETRIC PRINCIPLES

To produce a high-quality three-dimensional point cloud there are two important considerations: one is to ensure that there is adequate overlap between images for photogrammetric processing, and the other is that the images are of a high enough resolution to resolve

geologic structures on the bench faces. Based on experience, a 70% overlap in the forward and side directions is generally adequate. A 70% overlap means that for any given picture, the surrounding images each cover at least 70% the original image. Extra images are taken past the planned flight boundary to ensure that there is adequate coverage at the edges. The image quality is generally measured by a value called the ground sampling distance. The ground sampling distance is the real-world measurement of a camera pixel, usually in terms of centimeters per pixel.

The combination of the minimum required GSD, the percentage overlap, and the camera properties determine the perpendicular distance from the average dip of the slope, as well as the overlap percentage and the number, frequency, and location of where the drone needs to capture images.

Calculating the ground sample distance in both the forward and side directions is given in equation (1) and (2).

$$GSD_f = \frac{h \cdot S_h \cdot 100}{f \cdot I_h} \qquad\qquad \#(1)$$

$$GSD_s = \frac{h \cdot S_w \cdot 100}{f \cdot I_w} \qquad\qquad \#(2)$$

where:

GSD_f	=	Forward Ground Sample Distance (cm/pixel)
GSD_s	=	Side Ground Sample Distance (cm/pixel)
h	=	Perpendicular distance to ground (m)
S_h	=	Sensor Height (mm)
S_w	=	Sensor Width (mm)
f	=	Focal Length (mm)
I_h	=	Image Height (pixels)
I_w	=	Image Width (pixels)

Rewriting equations (1) and (2) to calculate the perpendicular distance to ground level is give in equations (3) and (4).

$$h = \frac{GSD_f \cdot f \cdot I_h}{S_h \cdot 100} \qquad\qquad \#(3)$$

$$h = \frac{GSD_s \cdot f \cdot I_w}{S_w \cdot 100} \qquad\qquad \#(4)$$

CNI uses the DJI Phantom 4 Pro drone, and has had good success in creating high resolution point clouds with Pix4D using a perpendicular distance to the slope geometry of 91 meters. The on-board camera has a sensor width of 13.2 mm, a sensor height of 8 mm, and a focal length of 8.8 mm. The resulting images have a width of 5472 pixels and height of 3078 pixels. Inputting these values yields a forward GSD of 2.69 cm/pixel and a side GSD of 2.49.

DRONEPLAN3D

In order to capture optimized imagery data for photogrammetry, CNI developed a program called DronePlan3D to design flight plans for the consumer grade drones. The program takes a three-dimensional DXF file, drone camera properties, and a scan boundary to generate a flight plan that follows the slope contour and adjusts the camera gimbal angle to the average slope within the camera field of view. To illustrate the DronePlan3D process, an example mine will be used. The elevation data used was retrieved from Google Earth and is publicly available. Figure 2 shows a plan view with satellite imagery of the north wall of an open pit slope with elevation contours.

The elevation contours need to be converted to a three-dimensional DXF, which can then be imported into DronePlan3D. Creating flight plans on up-to-date mine surfaces is critical in ensuring that good quality scans are achieved. One of the main features in this software package is allowing for any mine grid to be used with the integration of proj4 (PROJ contributors, 2019). With a custom proj4 string, any mine grid, including those with major orientation changes, can be used. At the time of publishing, many drones require that waypoint coordinates be in WGS84 latitude and longitude, which makes it necessary for the conversion.

Figure 2. Example cross sections cutting an open pit slope.

DronePlan3D overlays the three-dimensional DXF file on top of Google Satellite imager (as shown in Figure 3) to give visual confirmation that the coordinate conversion is accurate.
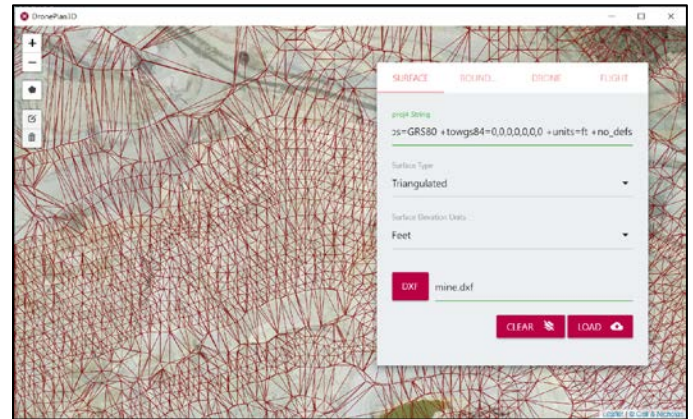

Figure 3. Three-dimensional DXF shown on Google Satellite Imagery.

The next step is to create a flight boundary polygon of the desired scan. The program was written to capture images so that the boundary would be adequately resolved. This flight boundary can be created in DronePlan3D or any DXF creation software.

After the boundary is selected, the drone model is selected, as shown in Figure 4. The presets for the drone models only change the forward and side field of view, so if these values are known, any drone can be used.

The last step is to define the perpendicular drone distance, flight azimuth, and takeoff elevation. The flight azimuth is the path up and down the slope that the drone will take, but is also what defines the azimuth where the camera will point.

The takeoff elevation is a critically important value that needs to be known because drones use a relative elevation based on the launch site.

Using the input information, the program then overlays cross section lines along the three-dimensional surface file. The cross sections are spaced such that the side overlap percentage is maintained for the defined drone type. Each cross section is then traced, and points are selected along the traceline to maintain the forward overlap percentage. At each of these points, all other points within the field of view of the drone camera are also selected and a best fit line through these points is calculated. Perpendicular to this best fit line is what is used for the camera gimbal angle. The drone position is then calculated by projecting a point at the camera gimbal angle from the original point along the slope that is equal to the perpendicular drone distance.

Figure 4. Drone properties in DronePlan3D.

The completed flight plan is then presented in the program, as can be seen in Figure 5. A three-dimensional representation of the flight plan is presented in Figure 6.
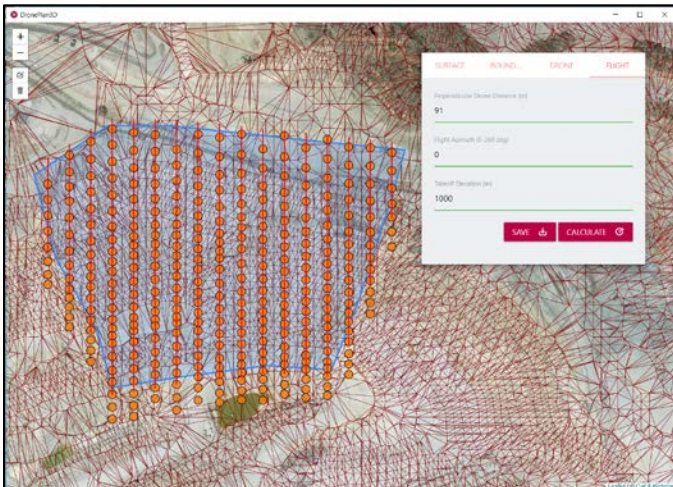

Figure 5. Completed DronePlan3D flight plan.

The flight plan file that is created in DronePlan3D is a .csv formatted file that includes each waypoint necessary to capture the images needed for photogrammetry. This information includes the latitude, longitude, relative altitude from the takeoff altitude, and camera gimbal angle. The flight plan is formatted to run in the Litchi flight control application, but can be easily converted to any other flight controllers if there is an option to define the drone position and camera gimbal angle for each waypoint.
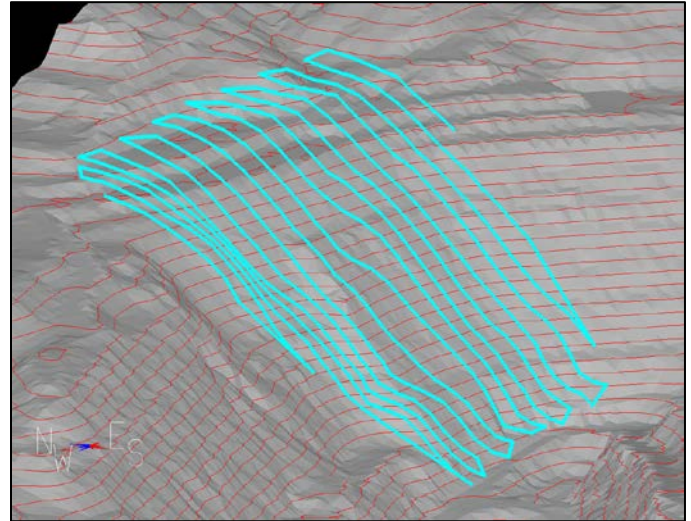

Figure 6. Completed three-dimensional DronePlan3D flight plan.

GEOTECHNICAL APPLICATIONS

The high resolution point cloud has many applications to aid the geotechnical professionals, including: 1) bench reliability audits, 2) rockfall analyses, 3) rock fabric mapping (cell or line maps), 4) large scale structure mapping, 5) deformation analysis (slope and underground displacements), and 6) accurate topographic maps. The advantages of virtual point cloud mapping are many. Detailed maps of inaccessible terrain due to active mining, rock fall hazards, or unstable slopes can be obtained with the point cloud data generated from a well planned and executed drone survey. With proper spatial registration, the measurements of structure orientations are better than field measurements. The ability to toggle between true and false color allow the mappers to identify subtle changes in the terrain and to make more robust mapping decisions. Mapping can be conducted at any time without relying on expensive and time-limited site visits. Analysis of the data at specific time intervals allows the analyst to identify the exact areas of slope displacements and determine the vectors of movement, which aids greatly in determining the mechanisms of slope instability. While drone data acquisition greatly enhances the interpretation of geology, field site visits remain invaluable to determine rock types and conditions of the rock quality, including strength of the rock fabric, the rock mass, and the faults.

Bench Reliability

A key to mining safe slopes is to understand the reliability of the designed catch benches. Slope audits that utilize point clouds generated from drone photos are ideal for this task because the blind zones encountered in stationary ground-based scanning methods are avoided. The audits performed on the data can be used to evaluate the current geotechnical designs and field implementation of the designs. If the designs are not being accomplished with the required reliability, the scans can be used to determine if the shortfall is due to geologic conditions or to some lack of care in the mining operation. Figure 7 shows an example of identifying the crest and the toe of muck on an excavated mine bench.

Rockfall Analyses

The key to analyzing rockfall is an accurate topographic map and an associated color point cloud. With these tools, the analyst can generate sections or three-dimensional surfaces for use in the analytical software. Figure 8 shows an example of a section generated from a surface made from a 1.5-meter contour interval from the point cloud DSM. The point cloud allows quick determination of potential unstable rocks and unstable bench crests. The size of the rocks can be easily determined.
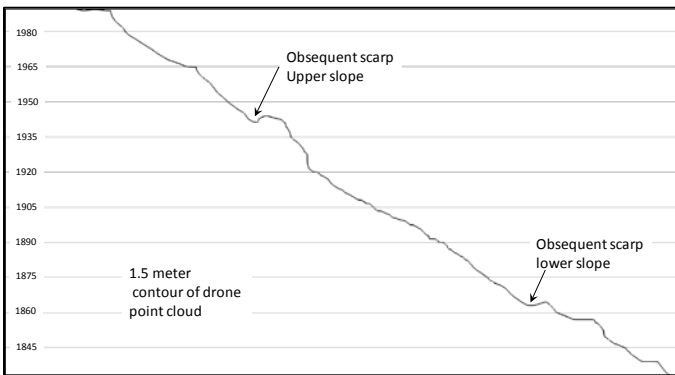
Figure 7. Bench audit example.

Figure 8. Cross section generated for rockfall analysis.

Rock Fabric Mapping

Due to the large size of the point clouds, it is best to segment the cloud into manageable cells for mapping rock fabric. This task is easily performed in point cloud processing software such as Maptek PointStudio and CloudCompare. Figures 9a and 9b shows the joint sets mapped with the plane orienting tool in CloudCompare and the sets mapped represented in a lower hemisphere pole plot. This bench face was a segmented section of a point cloud generated from flying at a perpendicular distance of 91 meters above the slope. The length and spacing of the joint sets can be measured from the point cloud.
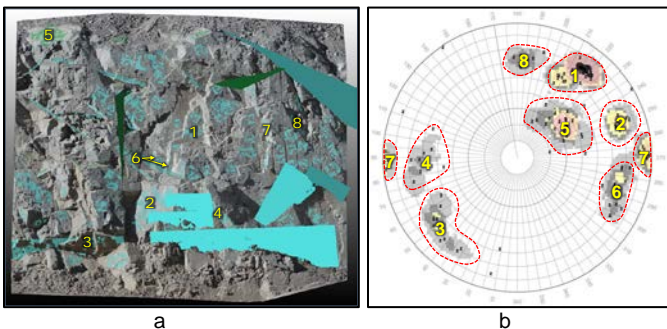

Figure 9. a) Joint sets mapped using the drone point cloud. b) Joint sets mapped using the drone point cloud on a lower hemisphere pole plot.

Large Scale Geologic Structure Mapping

Accurate mapping of large-scale geologic features such as faults, bedding, and contacts in mine pit slopes is often challenged by accessibility issues. Highwall mapping often relies on the projection of singular measurements from an accessible exposure, or highly interpretive mapping from a distance. Drone-based point cloud mapping allows the mapper to trace geologic structures in 3D while taking numerous, highly accurate measurements at any location along the span of a structure. Figure 10 shows a series of faults that were mapped on a point cloud using a 3D polyline tool in the software CloudCompare. The faults were delineated by their color contrast with the surrounding rock caused by brecciation and alteration, which is easily identified using the true-color point cloud.

Figure 10. Large scale geologic mapping of faults exposed in bench faces using a true-color point cloud.

Deformation Analysis

Deforming slopes or underground openings can be evaluated by overlaying spatially registered point clouds developed at a time frequency determined by the site requirements. The extents of the instability and the 3D vectors of displacement can be determined. Figure 11 shows the deformations within an area of an unstable slope over a period of 18 months on a false-colored gray-scale image showing the elevation gradient between points in the point cloud. The darker shades are steeper sections of the slope. Features in the point cloud that can be traced from scan to scan are used to generate the 3D vectors (azimuth, declination, and magnitude) which are represented by the arrows, and the magnitude of the vector is directly proportional to size of the arrow.
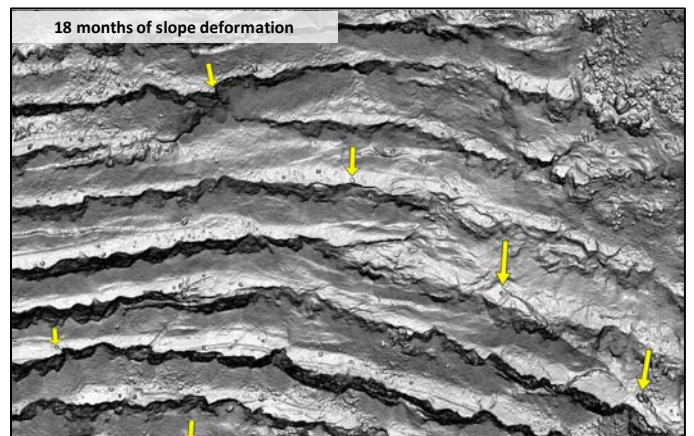

Figure 11. Example of 18 months of slope displacement.

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