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UAV-based Geotechnical Modeling and Mapping of an Inaccessible Underground Site

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ABSTRACT: Photogrammetry is becoming a more common method for mapping geological and structural features in underground mines. The issue of capturing geological and structural data in inaccessible areas of mines, such as those that are unsupported, remains even when utilizing photogrammetric methods; thus, geological models of mines are left with incomplete datasets. The implementation of Unmanned Aerial Vehicles (UAVs) underground has allowed for experimentation with photogrammetry conducted from a UAV platform. This paper contains the results of an investigation focused on collecting UAV-based imagery at underground locations within Barrick Gold Corporation's Golden Sunlight Mine in Whitehall, Montana, and the use of the imagery to produce 3D models for mapping geologic features. The primary components of the study described are the underground imagery acquisition experiences and a comparison of underground photogrammetry modeling with UAV imagery using two sets of software: a) ADAM Technology's 3DM CalibCam and 3DM Analyst and b) Bentley's ContextCapture for 3D modeling combined with Split Engineering's Split-FX for mapping. The lessons learned during this study may help guide future efforts using UAVs for capturing geologic data, as well as to help monitor stability in areas that are inaccessible.

1. INTRODUCTION

Current remote sensing techniques commonly used for capturing data in underground environments include using terrestrial or machine-mounted photogrammetry, light detection and ranging (LiDAR) point clouds, and forward looking infrared (FLIR) imagery (Gaich et al., 2015; Azhari et al., 2017; Liu and Kieffer, 2012; Aydan et al., 2017). LiDAR provides high-resolution point clouds and FLIR is currently being used to identify areas of loose rock based on thermal contrasts. The visible RGB (red, green, blue) values of the rock face, however, are not defined through either of these methods and tight fractures that are oriented perpendicular to the rock face can be difficult to identify. Photogrammetry allows for more comprehensive rock mass characterization, because three-dimensional (3D) point clouds can be generated using RGB metadata from the individual photos. Photogrammetry, with the aid of terrestrial lights, has successfully captured data in underground environments without sacrificing the visible color data or the ability to detect fractures with small apertures and/or orientations nearly perpendicular to the rock face.

Today, unmanned aerial vehicles (UAVs) have become a typical, terrestrial geological data capture platform for photogrammetry, LiDAR, and FLIR systems. In some UAV systems, simultaneous locating and mapping (SLAM) is combined with the imaging to allow the UAV to determine its own location on the map being produced from the imagery. The ability to rely on ground positioning system (GPS) signals for UAV stabilization and even for waypoint planning through mobile applications creates a fairly reliable method for capturing data from large areas in an efficient and safe manner. Many tools available commercially for above-ground environments utilize only GPS-signals for positioning the UAV. Underground flight is inherently riskier because GPS-signals are not available, and the UAV is being operated in a confined space.

In this study, the aim was to determine the viability of using a manually controlled, off-the-shelf UAV as a platform for capturing photogrammetric imagery in inaccessible underground areas that can subsequently be used for geologic and geotechnical characterization. The primary challenges to this are controlled flight in a GPS-denied environment and lack of illumination. An on-board camera, obstacle sensing and detection system, and lighting system were added to the UAV for successful data collection. Imagery was captured at several locations (including a large unsupported stope) within Barrick Gold Corporation's Golden Sunlight

Mine (GSM), an underground mine in Whitehall, Montana. GSM currently uses a LiDAR scanner mounted on a telescoping boom to generate 3D point clouds of the stope. This technique is limited because there are few draw points into the stopes, and any volume of the stope outside of the line-of-sight of the LiDAR at the draw point is not captured.

A LiDAR scanner cannot provide the data that a photogrammetric model can provide to a geotechnical engineer, because point clouds generated from underground data typically lack RGB metadata. Even though LiDAR is able to produce a denser point cloud than that of photogrammetry, it can be more difficult to map the geometric fracture orientations within the rock mass. Additionally, the RGB values provided via photogrammetry allow for data like geologic contacts to be collected, where no other geologic data are available. The UAV-based photogrammetric system is not a perfect system either, but it could aid in predicting major ground failures.

2. EQUIPMENT & SOFTWARE

Several companies have developed UAVs for flying in confined spaces, including underground environments. Flyability's Elios UAV (Elios, 2018) is enclosed within a rotating cage that absorbs and transfers energy during a collision, allowing the UAV to stay upright after contacting an object; unfortunately, the cage interferes with its usefulness for photogrammetry because of its presence in the imagery. Inkonova's TILT Ranger UAV (TILT Ranger, 2018) is a custom drone platform dedicated to underground mine mapping with a LiDAR, but cannot be considered an "off the shelf" UAV.

The DJI Matrice 100 (M100) platform was chosen for this study because of its affordability, size, sensing system compatibility, and customization capabilities. Additionally, when the M100 was chosen, it was one of the only customizable UAVs that had an off-the-shelf sensor system package that could be added onto the platform for obstacle sensing and avoidance. The M100 utilizes the DJI Guidance obstacle sensing system, which works in tandem with the built-in flight controller to aid avoiding obstacles detected at a user-defined distance. Stereo cameras mounted to point ahead, behind, on both sides, and below the UAV are used in conjunction with ultrasonic sensors to detect obstacles (DJI, 2015). One drawback of this system is the lack of obstacle detection above the UAV which is not needed for traditional above-ground scenarios. Blind spots also exist around the legs of the UAV, because of the camera's 60-degree horizontal field-of-view (FOV) and 56-degree vertical FOV (Fig. 1).

When obstacles are sensed at the minimum user-defined distance, the UAV stops and may even slightly pull away from the obstacle in the opposite direction of detection. The UAV will no longer allow movement in the direction of the obstacle, until it is at the minimum distance from the obstacle. In order for the obstacles to be detected, DJI states that a lux (measured in lumen/m^2) ranging between 10-10,000 is required (DJI, 2015). During the course of this research, it was found that the minimum of 10 lux is not an accurate value for determining lighting required to sense obstacles; a higher lux value is required for proper functioning of the system. When lighting is sufficient and the Guidance system senses an object, a warning of the approximate distance from the object is transmitted to the UAV's remote controller. The warnings display on top of the real-time imagery. The real-time data feed is sent through a 2.4 GHz connection between the UAV and the remote controller. The DJI GO application is necessary for capturing data during operation of the aircraft when a camera is connected.

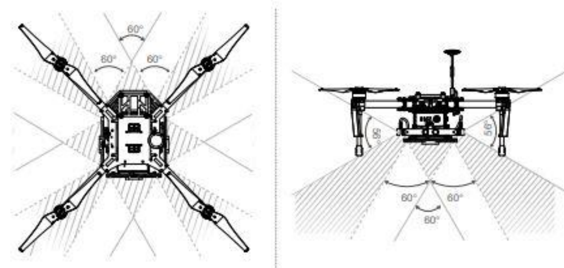

Fig. 1. DJI Guidance system cameras FOV (DJI, 2015). Top view (left) showing horizontal blind spots and side view (right) showing vertical blind spots.

Real-time imagery can also be viewed through the connected mobile device in the DJI GO app. The imagery is reduced to a size that can be quickly transferred to the remote controller and is saved onto the mobile device, in this case an iPad Mini 4. The imaging device used is a DJI Zenmuse X3 digital camera. It has the capabilities of recording video or taking still photographs, both with adjustable settings. It has a CMOS sensor size of 6.17 x 4.55 mm, a fixed lens at 3.6 mm (35 mm format equivalent of 20 mm), and an f-stop of 2.8 at a focal length of infinity. The camera is connected to a 3-axis gimbal that allows for the camera to be tilted up to 120-degrees and rotated 360-degrees (DJI Inspire 1 User Manual, 2015). A micro-SD card is used to store the full-sized formatted imagery data and other flight details.

Lighting requirements for the system are dictated by the Guidance system and the imagery. The DJI Guidance system specifications state that a lux greater than 10 is required for visual obstacle detection (DJI, 2015). Through trial and error, it was determined that 10 lux of light projected onto the surface captured by the stereo-cameras was not sufficient for the DJI Guidance to detect obstacles. As a result, several available lighting systems were tested. It was found that the Guidance would not function at less than 105 lux when 3 m (10 ft.) away from the rock face. The lights that produced that lux reading, two Lume Cubes, did not produce a strong enough lux at a distance greater than 3 m (10 ft.) for obstacles to be detected. It was determined (Turner et al., 2018) that two Stratus LED Arm Modules produced a measured lux of 550 at a distance of 3 m (10 ft.) from the rock surface and a lux of 105 at a distance of approximately 6.5 m (21 ft.). Consequently, to provide adequate lighting, the two Stratus LEDs Arm Modules were used.

If the visual sensing system is not able to detect an object due to darkness, it will drift toward that direction to avoid other obstacles. Since lux decreases with an increase in distance between the UAV-mounted light source and lit objects in a completely dark area, less lux is available for obstacle avoidance. In an attempt to avoid issues with uncontrollable drifting due to darkness, lights that greatly exceed the minimum lux requirements were chosen. The Stratus LED Arm Modules, shown in Figure 2, are made up of a 100 Watt 13,000 lumen 5600K CRI LED emitter, a heat sink, an LED driver, and a LiPO battery (ARM LED, 2018). Due to UAV payload limitations, only two lights were able to be attached. One LED was mounted in the forward-facing direction and the other, with the parabolic reflector, was pointed downward. The parabolic reflector, concentrates the beam angle of the light at 60-degrees, versus 170-degrees without the reflector. The smaller beam angle allows the downward facing light to be projected over a greater distance (respectively creating a higher lux) allowing the UAV to “see” the ground surface from larger heights. As long as the UAV can sense the ground surface, it remains stable when hovering.

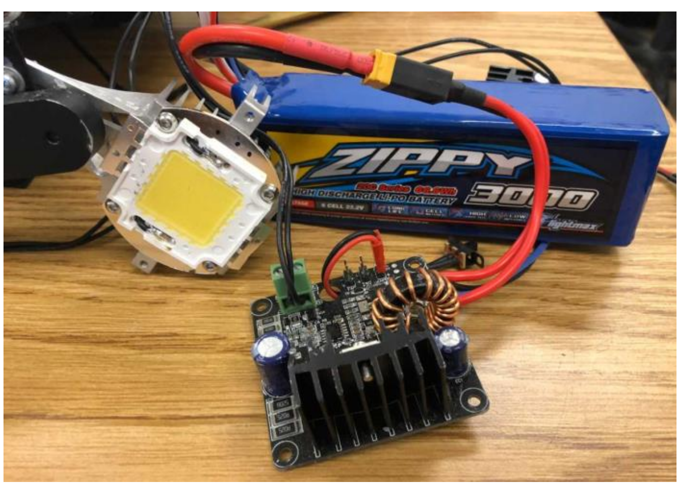

Fig. 2. Stratus Arm LED module used on the UAV.

In order for the parabolic reflector to face downward from the arm of the UAV, longer legs were necessary. Longer legs can be purchased through DJI with a Zenmuse X5 Gimbal Mounting Kit but are not sold separately. As an alternative, custom carbon fiber legs were designed and constructed using automobile oil drain plugs to create the connectors to attach the legs to the UAV. Figure 3 shows the machined drain plug attached to the leg. The shock absorbing devices from the original DJI legs were attached to the bottom of the new legs.

Fig. 3. Machined drain plug used to serve as UAV leg attachment piece.

3. PHOTOGRAMMETRY

Photogrammetry is a science that uses two-dimensional (2D) overlapping imagery to resolve three-dimensional (3D) locations of the object(s) being captured (Adam Technology and Birch, 2010). Using photogrammetric techniques, two images with significant overlap horizontally and vertically, called stereopairs, can be used to recover 3D data that are lost in 2D images. The imaging device receives light bouncing off of the object through its lens to the sensor. At that point the origin of the light reflecting onto the sensor is unknown. When another image is captured from a different location and light is received through the lens and onto the sensor again from the same location, a unique 3D location can be determined. The 3D location is where the light rays from the two different camera positions intersect. The accuracy of photogrammetry is highly configurable, in theory. Accuracy increases with smaller ground pixel sizes, reducing the error ellipse created between the two light paths. Though, without precise control over the imaging device’s distance-to-base ratio, such as when flying a UAV, the accuracy cannot be configured as easily.

For the purpose of this research, it is important to delineate the distinction between two terms that are often used interchangeably. The term “modeling” refers to the process of creating a 3D surface of the area being captured, with the images projected onto that surface. The term “mapping” is reserved for the process of identifying geologic features and assigning 3D quantitative values to geological structural data present within the model (e.g. dip and dip direction of a joint surface).

After testing various photogrammetry software packages, two were selected for inclusion in this study, to compare modeling and mapping processes and outputs. Adam Technology's 3DM Analyst and 3DM CalibCam were selected because Montana Tech owns these licenses and the researchers were the most familiar with them. Bentley ContextCapture was also selected because out of the various photogrammetry packages tested, it was able to complete the most complete 3D models of the underground environment using video imagery. Each software has its own requirements for creating 3D models, as well as its own advantages and limitations.

Adam Technology's 3DM Analyst and 3DM CalibCam require an overlap between stereopairs of 60-80% (ADAM Technology, 2010). This software suite was developed over a decade ago and was originally designed to be optimized for creating models from a minimal set of terrestrial photos taken from preferred locations. To create a model, the software prefers to have a calibration file for the associated camera and lens with which the project photography is taken. A lens calibration is created by performing a relative interior orientation with a group of photos that overlap. The photos used for the calibration also need to capture an area that is a similar distance away from the camera (similar to the project) and has varying depth. A set of 12 overlapping photos from one of the GSM flights (the stope flight) was used for the camera lens calibration. Calibrating the lens helps to better define the interior orientation of the camera and helps to reduce distortion that the lens imposes on the imagery.

The other photogrammetry software used, Bentley's ContextCapture, requires approximately 50-80% overlap in between images for 3D model construction (Bentley, 2018). This is a newer software package that was developed to be optimized for UAV-based photogrammetry that produces many images (but not necessarily images captured at ideal positions). The software uses a relative aerotriangluation to determine the relationships between the images. All images that were used in the model were used for the aerotriangulation.

In terms of photogrammetry, georeferencing refers to assigning coordinates to points in images that have been surveyed on a specified coordinate system. By assigning the actual positions of the points on a coordinate system, the imagery is scaled to the actual life-size scale and oriented correctly in space. With a correctly-oriented life-size scaled 3D model, measurements can be taken on the 3D model and will represent the actual measurement, as if it were taken in the field.

Typically, surveyed control point markers or spray painted points (Fig. 4) are used for assigning coordinates to points for creating absolute underground 3D models. It is good practice to spread the control points across different areas of the model. When control points are distributed throughout the model, distortion is reduced, providing a truer representation of the area being modeled. However, spreading control points across an area that cannot be accessed is challenging and may not be possible. In this project, a paintball gun (Fig. 5) was used to make paint marks on the rock faces that were within the area to be modeled and also within line-of-sight (LOS) of the surveying equipment.

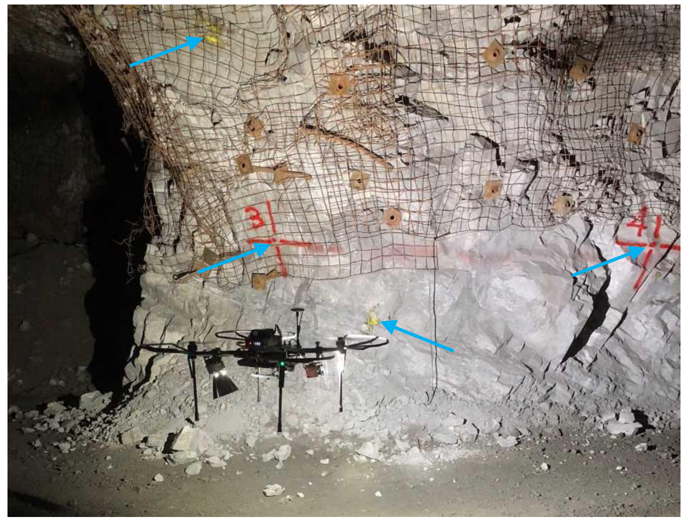

Fig. 4. Control points marked on the rib of the mine drift marked with spray paint (in red) and marked using a paintball gun (in yellow).

Fig. 5. Elizabeth Russell using the paintball gun to mark control points in areas that are out of reach.

4. UNDERGROUND DATA CAPTURE

Prior to capturing data in an inaccessible underground stope, imagery was captured while flying the UAV in and out of LOS in drifts and intersections at GSM. These flights were performed to confirm that the DJI Guidance system was functioning properly and to delineate the range of safe operations for collecting structural data on a UAV-based platform in the underground environment.

Additionally, a handheld UAV imaging experiment was conducted in a drift at GSM to determine the preferred frame rate of image capture, file format in which the imagery is captured, and resolution at which the imagery is captured. It was concluded that for the underground imaging and in order to accomplish the project goals, a frame rate of 60 frames-per-second (fps), and a 1920 x 1080 resolution were appropriate. When flying out of LOS around the corner of an intersection of connecting drifts, no communication errors were experienced between the UAV and the remote controller (or the live-feed imagery). The UAV reached up to about 38 m (125 ft.) out of the pilot's LOS during the test. To clarify, the measurement of 38 m is the total distance to the end of the drift in which the UAV was flown and not necessarily the maximum distance that could have been reached before the remote controller lost signal to the UAV.

During this same experiment, the georeferencing technique was confirmed to work as well. For the absolute models, the paintball gun technique was developed and tested to ensure that control points could be added to areas that are within LOS of the surveying equipment, but located within the inaccessible area being modeled. To determine the coordinates of paintball marks located within the stope, a resection was performed using a Trimble total station, and then the positions of the paintball marks were measured using the reflectorless total station. A resection uses two (or more) known points to find the coordinates of a third. The third point is the location of the total station. Once that location's coordinates were determined, then the points within the stope could be measured using the reflectorless total station. It was helpful to have one person use a powerful flashlight to illuminate the paintball marks while another person measured them using the total station. Also, it was found that the survey equipment needed to equilibrate with the temperature and humidity underground, so that condensation would not develop on the lenses of the total station.

4.1. Flight in the 815-102 drift

After a number of successful flights had been logged underground and the preferred imaging format was determined, the UAV was flown in the "815-102" drift at GSM. The UAV was not flown out of LOS in this particular drift. The main goal of this flight was to capture overlapping imagery in an environment similar to the planned stope flight. The imagery was captured successfully, but there was one incident in which the behavior of the UAV did not correspond with the remote controller commands being given. The UAV was being drawn closer toward the rib, and it would not respond to attempts to direct it away from the rib for 15 seconds or so. The problem was not diagnosed, and was dismissed once the UAV responded to the remote controller again.

The overlapping imagery was used to create a model of the 815-102 drift to verify that underground UAV imagery could be used to create an adequate model that can be mapped. Other reasons for demonstrating the ability to successfully fly and collect data in drifts are a) the ability to inspect a drift after a blast where the ground is unsupported can be advantageous, and b) progressive models can be made with each new blasted portion of the advancing drift, serving as a record of the blasts and a tool to allow mapping of the geological and geotechnical features of the face.

4.2. Flight in the NEV stope

After successfully flying in the 815-102 drift, the UAV was flown in the "NEV" stope, entering the stope from the first draw point. The stope was 6 m (20 ft.) wide, 50 m (150 ft.) tall, and 120 m (400 ft.) long. Figure 6 is a diagram of the NEV stope, showing the drawpoint locations with respect to the stope and drift access.

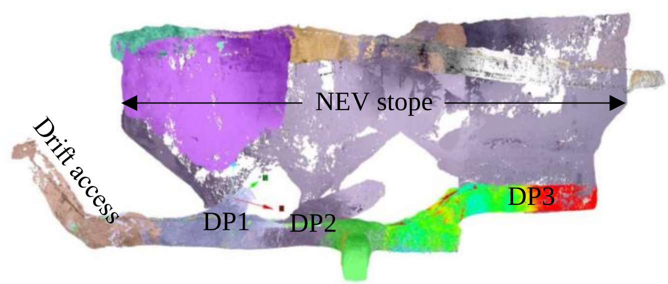

Fig. 6. Side view of the NEV stope, including the access drift and the three draw point locations that can be used for access to the stope (B. Dale, GSM, modified).

Video imagery in the stope was collected in 1920 x 1080 resolution at 60 fps. Points were marked using paintballs and were measured using the paintball georeferencing technique. The two known points used for the resection were control points that the mine surveyor had installed as a reference for underground personnel. The ground control points that were created successfully with the paintball gun and calculated are listed in Table 1.

The locations of the measured control points are shown in Figure 7 with respect to the UAV starting point (outside the first draw point of the NEV). GP3 was not easily distinguishable in the imagery once it came time to build the models, so it was left out. The other three control points were used for model making. It is important to note that three control points is the minimum number of control points necessary for building a georeferenced 3D model. For an area of the size captured, a couple more control points would have been ideal.

The intended flight path was to first cover the lower portion of the stope in an elliptical motion, and then to move up vertically to capture overlapping data with the same elliptical pattern. The initial portion of this spiral flight path worked well, but once the UAV was out of LOS, it proved difficult to keep track of where the UAV was with respect to the starting position. Significant amounts of water dripping from above, along with a large amount of dust in one portion of the stope, caused additional issues with keeping track of the UAV's position. After 30 seconds or so the UAV was located by using the downward facing light as a visual reference and the pilot continued to operate the UAV, occasionally moving the camera to capture more imagery while hovering. The obstacle detection system was operating for most of the flight, but in the last few seconds the UAV was drawn into the rock face, similar to a previous observation when flying in the 815-102 drift. While flying in the stope, the pilot attempted to direct the UAV away from the wall, but it did not respond. At this point, the UAV was out of LOS and was facing in the opposite direction of the take-off position (facing the pilot). The UAV impacted the wall and crashed, but fortunately rolled down the muck pile and was recovered safely. Enough imagery was captured to build an incomplete model of draw point one of the NEV stope at GSM, and it provides more geotechnical data than was available without the model.

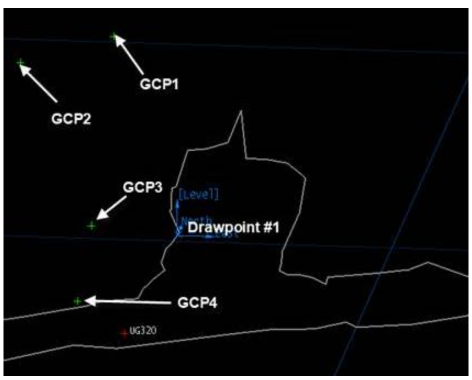

Fig. 7. Looking obliquely north in Maptek's Vulcan at the four ground control points measured from draw point one (R. Turner, GSM, modified).

5. RESULTS/SOFTWARE COMPARISON

Using data collected during flights in the 815-102 drift and the NEV stope at GSM, models were constructed using different software for comparison:

- **(i)** Adam Technology's 3DM CalibCam, DTM Generator, and 3DM Analyst
- **(ii)** Bentley's ContextCapture, Agisoft PhotoScan and Split Engineering's Split-FX

Successful models of the 815-102 drift were built and mapped (Figures 8 and 9). Only one model of the stope imagery was successfully built (Figure 10) and few features were mapped. A more complete model is expected once imagery is available from future flights.

In both software packages used for data processing there is the option to run the model as a controlled model, defined by georeferenced or defined control points, or as a relative model, defined by matching points that the software finds between images. For this project, the models of the 815-102 drift were constructed as relative models, while the NEV stope models were constructed with a georeferenced orientation on the local mine coordinate system. Georeferenced models are also referred to as absolute models.

In Adam Technology's software package, 3DM CalibCam has the function to build 3D point clouds, meshes, and surfaces. The DTM Generator first generates sections of digital terrain models (DTMs) using the point clouds from each image strip, then merges all of the DTM pieces into a single DTM of the entire area. Last, 3DM Analyst is used to map 3D structures on the merged model. As shown in Figure 8a, when the model DTM is merged, the imagery is not projected onto the surface; however, the imagery can be projected onto the surface when loading all of the individual DTMs used to create the merged model (Fig. 8b).

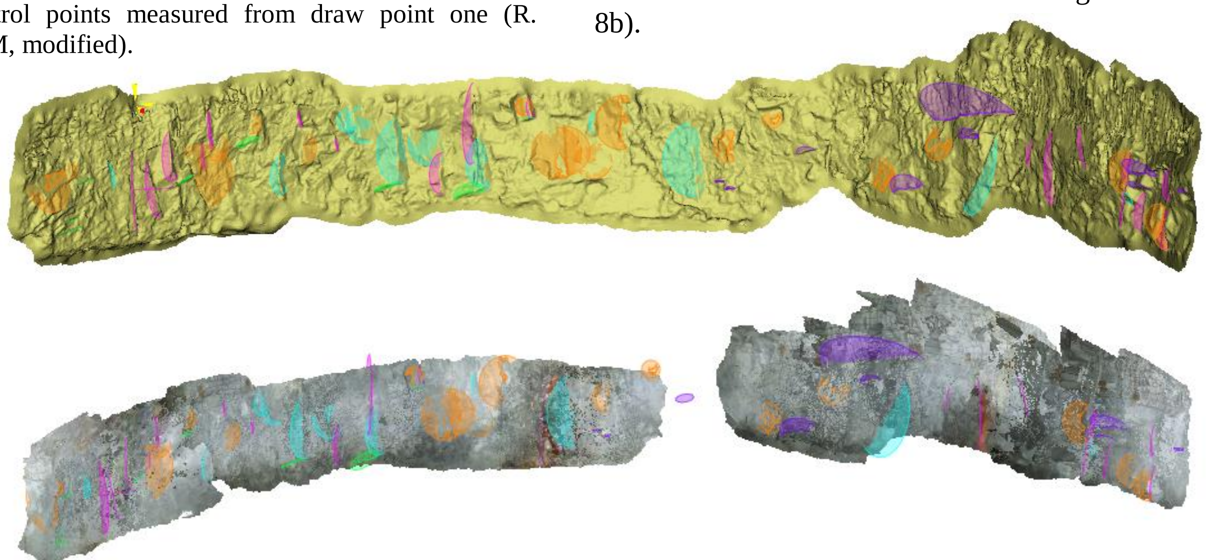

Fig. 8. *Top*: Merged DTM model of the 815-102 drift with mapped structures at GSM that does not show the projected imagery. *Bottom*: DTM pieces loaded together, so that the imagery is projected onto the surface of the model with mapped structures – seven of the DTM pieces were unable to load creating a hole in the model.

The merged DTM was created with relative orientation, which resulted in a curved model shape. Without defined ground control points, the model was unable to accurately represent the (straight) drift as it is found underground. The stereonet for this model is provided in Figure 9, but is not an accurate representation of fractures in the drift due to the fact that the model is not in an absolute orientation. In addition, the curvature of the model causes erroneous variation in orientation of joints that are closely aligned in real space.

A comparable 3D model was built of the 815-102 drift using Bentley's ContextCapture (Fig. 10) using the same frames as were used in Adam Technology. The images were assigned to generate a model with a relative orientation in the aerotriangulation stage of the model build. The model created with Bentley's ContextCapture was judged to be more successful in capturing the shape of the 815-102 drift.

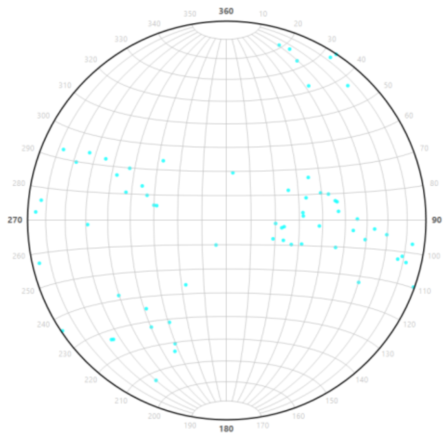

Fig. 9. Stereonet of structures (with relative orientation) mapped on the 815-102 drift located at GSM using Adam Technology.

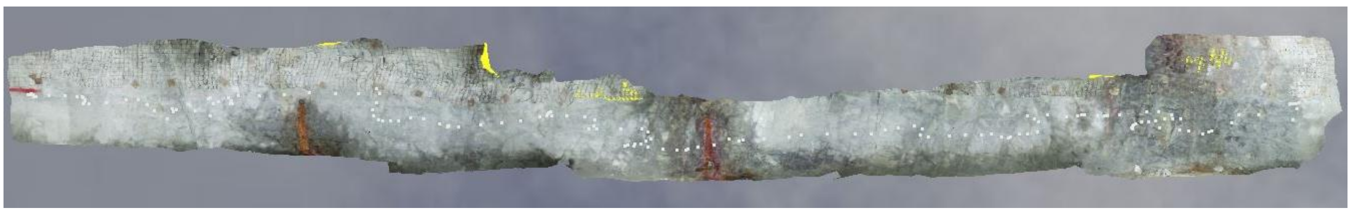

Fig. 10. Model of the 815-102 drift at GSM created using Bentley's ContextCapture.

Table 1. Ground control points (GCPs) that were measured in the stope using the Trimble Total Station and two known survey points. These values are in the local mine grid.

GCP ID	Easting (ft)	Northing (ft)	Elevation (ft)
GCP1	22966.853	26061.000	4346.021
GCP2	22955.983	26046.395	4344.019
GCP3	22968.403	26022.349	4328.174
GCP4	22967.294	26016.298	4319.216

Mapping features was not available in ContextCapture, so mapping was accomplished using Split Engineering's Split-FX. The point clouds created in ContextCapture were exported as a .las file and imported into Agisoft Photoscan, so that an ASCII ".pts" file could be created. The ".pts" file was then imported into Split-FX and structural features were mapped. The stereonet from the ContextCapture model still does not project the fractures mapped in the true orientation, because the model is on a relative scale. Mapping in Split-FX was found to be more difficult than in 3DM Analyst, because the model is much harder to navigate than in 3DM Analyst.

The NEV stope was modeled and mapped using both software packages, with attempts to create absolute rather than relative models. Frames from a four minute flight in the stope were selected and modeled in both 3DM CalibCam and ContextCapture. Each model used three of the four points measured with the Trimble total station. One of the points was not used, because it was not clearly visible in the imagery. The model using CalibCam was unsuccessful, but the ContextCapture model was built successfully. The model is incomplete in that it has holes where either bad data exists or no data exists (Fig. 11).

The general shape of the first draw point can be clearly seen in the model, though. Structures were mapped in the point cloud model using Split-FX, but few visible surfaces were identified (Fig. 12). With better data and an adjusted flight plan, it is possible that a better model can be created and more features will visible to be mapped.

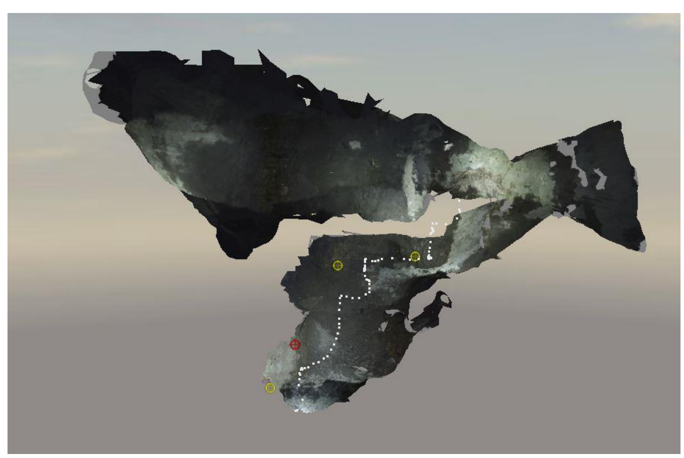

Fig. 11. ContextCapture model built from a UAV flight into the first drawpoint of the NEV stope at GSM (GCP1, 2, & 4 in yellow; GCP3 in red; white dots represent the UAV route).

Working with both software packages, it became apparent that the underground models are more reliably built using Bentley's ContextCapture. The software package is straightforward and generated models can easily be navigated. Adam Technology's suite of software for building the DTM is not as intuitive to use as ContextCapture and is less straightforward on which steps to take. Adam Technology was designed for very precise data modeling, but UAV-based imagery from manual flights does not allow for such precision. It is convenient, though, that Adam Technology has the ability to map structural data within its software. Having to convert the exported Bentley point cloud using a separate software is a hassle and would not be an option if Agisoft PhotoScan was not available. Mapping using Split-FX was much more difficult than it was using 3DM Analyst. In Split-FX, the point cloud was slow to respond to manual rotation and zooming. When trying to pull the model in a certain direction, the model was moved in a different direction. Lack of experience with the Split-FX software is most likely contributable to these issues as well. On the other hand, mapping features in 3DM Analyst was fairly easy to navigate.

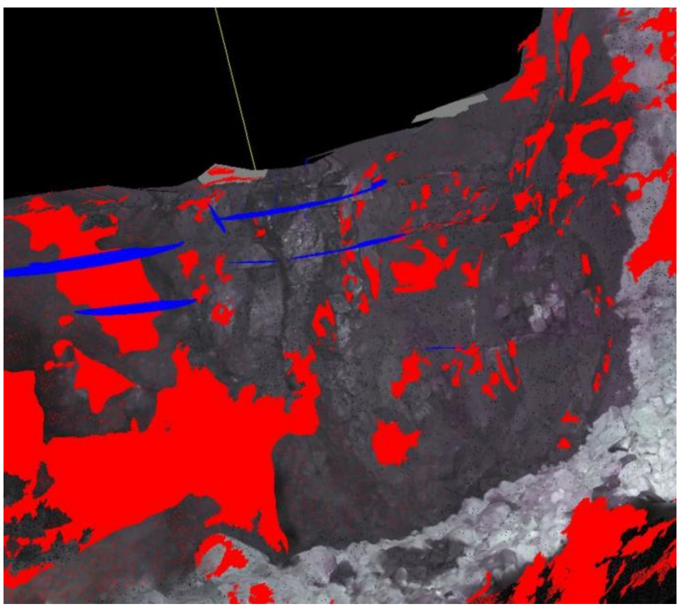

Fig. 12. ContextCapture model built from a UAV flight into the first drawpoint of the NEV stope at GSM with mapped structures (created by Ryan Turner).

6. CONCLUSIONS & FUTURE RESEARCH

From the data collected thus far, it can be concluded that neither using Adam Technology's software nor using Bentley's ContextCapture with Split Engineering's Split-FX is a superior underground photogrammetric modeling and mapping software. Without an absolute orientation of the model, Context Capture seemed to produce a more reliable model than 3DM CalibCam and the DTM Generator. Bentley's ContextCapture does seem to be a more appropriate software for underground UAV photogrammetric model making, because the locations of camera stations and the distance from the object being captured does not need to be specific, like in Adam Technology. ContextCapture did successfully build a model of the NEV stope from which geotechnical data was collected. Using the geotechnical data for kinematic analyses would determine the stability of the stope. When manually mapping geotechnical data, though, Adam Technology's 3DM Analyst is much easier and efficient. No solution is perfect, but the data measured from the mapped models can potentially create a safer mine. Without using a UAV-based system to capture geotechnical features in inaccessible areas of mines, geotechnical data in those areas are unknown. With a void in the ground as large as the NEV stope, GSM needs to understand the rock mass and its inherent stability as completely as possible. With improvements in flight planning and data capture, 3D stope models and mapping geotechnical features will fill in the data gaps.

In the upcoming months, additional stope flights will be carried out to collect supplementary data. The data collected from the next flights are expected to be higher-quality than that of the first stope flight. Flights will be planned around the shape of void being videoed and to start where the greatest extent of LOS exists for all parts of the flight. Imaging will begin while the UAV is still low to the ground, and the pilot will capture all data straight ahead and to the sides initially. Then, the pilot will work on capturing data with the drone turned around 180-degrees and up higher in the stope. Another possible step to be taken prior to the main data collection will be to use the UAV to scope out defining features located in different areas of the stope. That way the pilot will have a better idea of the UAV orientation once it is out of LOS. In addition to the pilot, a separate remote controller will be used for data collection (e.g. for movement of the camera). The second remote controller, termed a "slave remote" will be controlled by another team member. Clear communication between the pilot and the person operating the slave remote controller will allow for much smoother and successful data collection.

Additional options being considered for improving data collection include:

- using beacons to extend the range of communication between the UAV and remote controller(s)
- using an Inkonova TILT Ranger UAV that is customized to achieve the project goals, so that obstacle avoidance is not contingent upon the cooperation of the DJI Guidance system
- using a UAV LiDAR, SLAM, and/or a similar product for
  (a) utilization of an autonomous flight path,
  (b) obstacle avoidance,
  (c) generating a dense point cloud, and
  (d) use in tandem with a time-synchronized camera for assigning RGB values to the point cloud.

It is anticipated that using a LiDAR system with SLAM and a time-synchronized camera will be the most ideal data collection system. Using all of these technologies in tandem will allow for a very dense point cloud (via LiDAR), obstacle detection/avoidance and autonomy (via SLAM), and more detailed data with the RGB values assigned to each point (via camera). Multiple companies have accomplished different portions of this ultimate underground remote sensing technique, and Montana Tech is collaborating with these companies to develop a system that can provide useful geotechnical data collected in inaccessible underground areas via UAV.

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REFERENCES

1. ADAM Technology. 2018. Retrieved on 22 September 2017, from https://www.adamtech.com.au/

2. ADAM Technology. 2010. *3DM Analyst Mine Mapping Suite 2.3.4 User's Manual*. Revision 1.0.137.

3. ADAM Technology and Birch, J. 2010. *Using 3DM Analyst Mine Mapping Suite for Rock Face Characterisation [PowerPoint Slides]*. Retrieved on 19 March 2018, from https://www.adamtech.com.au/3dm/Golden%20Rocks%20(ADAMTech).ppt

4. ARM LED. 2018. Retrieved 15 March 2018, from https://www.stratusleds.com/arm-led/

5. Aydan, Ö., N. Malistani, and N. Tokashiki. 2017. The possibility of infrared camera thermography for assessing the real-time stability of tunnels against rockburst. *Proceedings of the Fifty-first US Rock Mechanics/Geomechanics Symposium, San Francisco, 25 – 28 June 2017*. Paper 17-479.

6. Azhari, F., S. Kiely, C. Sennersten, C. Lindley, M. Matuszak, & S. Hogwood. 2017. A comparison of sensors for underground void mapping by unmanned aerial vehicles. *Proceedings from Underground Mining Technology 2017, Perth.*

7. Bentley. 2018. *ContextCapture User Guide*. Updated 19 January 2018.

8. DJI, 2015. *Guidance User Manual*. Version 1.6, 21-22. Shenzhen, PRC

9. DJI, 2017. *DJI Inspire 1 User Manual*. Version 2.2, 36-37. Shenzhen, PRC

10. Elios – Inspect & Explore Indoor and Confine Spaces. 2018. Retrieved on 15 March 2018 from https://www.flyability.com/elios/

11. Gaich, A., G. Lenz, P. Wagner, M. Potsch, M.R. Henzinger, and W. Schubert. 2015. Circular 3D images from TBMs. In *Proceedings of the Thirteenth ISRM International Congress of Rock Mechanics, Montreal, 10 – 13 May 2015*.

12. Liu, Q., and D.S. Kieffer. 2012. Digital tunnel mapping using terrestrial LiDAR – a case study. In *Proceedings of Eurock 2012 – the 2012 ISRM International Symposium, Stockholm, 28 – 30 May 2012*.

13. TILT Ranger. 2018. Retrieved on 15 March 2018, from http://inkonova.se/tilt-ranger/

14. Turner, R.M., N.P. Bhagwat, L.J. Galayda, C.S. Knoll, E.A. Russell, and M.M. MacLaughlin. 2018. Geotechnical Characterization of Underground Mine Excavations from UAV-Captured Photogrammetric and Thermal Imagery. *Proceedings of the 52nd US Rock Mechanics/Geomechanics Symposium, Seattle, 17-20 June 2018*. Paper 18-508.