USE OF DRONES IN AN UNDERGROUND MINE FOR GEOTECHNICAL MONITORING

By

Priyanshu Raj

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As members of the Master's Committee, we certify that we have read the thesis prepared by PRIYANSHU RAJ, titled USE OF DRONES IN AN UNDERGROUND MINE FOR GEOTECHNICAL MONITORING and recommend that it be accepted as fulfilling the dissertation requirement for the Master's Degree.

Dr. John Kemeny Date: 5/13/19

Dr. Kwangmin Kim Date: 05/13/2019

Dr. Moe Momayez Date: 05/13/2019

Final approval and acceptance of this thesis is contingent upon the candidate's submission of the final copies of the thesis to the Graduate College.

I hereby certify that I have read this thesis prepared under my direction and recommend that it be accepted as fulfilling the Master's requirement.

Date: 5/13/19

John Kemeny
Master's Thesis Committee Chair
Department of Mining and Geological Engineering

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ABSTRACT

Geotechnical monitoring is a significant aspect of mining. This includes traditional monitoring with extensometers and stress meters, as well as new technologies which include Lidar, Radar, advanced wireless sensors, and many other new technologies. Underground mining has unique and significant safety hazards compared to surface mining, due to high stress concentrations, weak rock masses, and limited access and air quality. Underground mining methods that utilize large open stopes is one example. After each production blast in open stopes, for example, the rock can become unstable due to excessive vibrations. Since not all the areas inside stopes are accessible, it can be unsafe to put costly production equipment like Load Haul Dump (LHD) vehicles and drilling jumbos inside the stopes. Secondary blasting also becomes hazardous as it requires mining personnel to enter hazardous areas. Traditional monitoring equipment for stope monitoring is ineffective and impractical in most cases, due to the difficulties in placing the monitoring equipment inside unsafe areas of the stopes.

The use of a drone can improve safety compared to other surveying systems. In addition, underground monitoring utilizing drones delivers fast results, gives real-time results, and minimizes human exposure in unsafe underground conditions. The mining industry already is benefiting from the rapidly advancing drone technologies. However, most of the drone use now is for is for surface mining, and its use in underground mining is still an area that needs significant research and development. A drone stabilizes itself using GPS, but in certain places and locations, this is not always possible; for example, under a bridge, inside a building or in an underground mine. Also, it is not safe for human personnel to enter all locations in a mine because areas can be dangerous due to loose hanging rocks and unsafe air quality. The unavailability of GPS, the low light conditions, and the confined spaces make it very difficult and challenging to use drones in an underground space, and hence University research in this area is both important and necessary.

The research described in this thesis includes the following four areas:

1. Purchasing a drone and demonstrating that it can be controlled and used to capture images in an underground environment with confined space.

2. Developing a solution for drones to work in the dark underground mine environment with the use of specially designed lights attached to the drone.
3. Optimizing the settings in the drone camera to capture images of significant quality and quantity to producing high-density three-dimensional point clouds.
4. Demonstrating that the point clouds produced from underground drone monitoring are enough to extract geotechnical rock mass characteristics and rock mass movement using point cloud processing programs.

1. INTRODUCTION

Since the beginning of human civilization, people have been using mining techniques to access minerals present in the earth crust. In the earlier days, the process of mining was not as safe because people were not aware of the way to extract minerals safely. In the initial years, miners used ancient tools for digging and mine openings were excavated using manual labor which was time-consuming. During the 16^{th} century, gunpowder was first used by miners to break rocks. The innovation spread quickly throughout Europe and the Americas. However, with the progress of time society has developed a more safe and accurate way of exploring and extracting valuable minerals from the earth. With the advancement of time and associated increasing level of education, people started having a deeper understanding of mining with topics such as geology, mine planning, rock mechanics, surveying, sustainable resource development, metallurgy, mineral processing and many other subjects.

As the 21^{st} century begins, mining as a global enterprise is becoming more and more important, and with the development of new technologies, the ability to mine complex and deeper ore bodies also increases. Companies are leveraging the academic institutions to fully harness creative research ideas and start developing more efficient and innovative mining methods to extract minerals more economically while at the same time increasing safety and decreasing environmental harm. According to an article published in BATS Magazine, tens of thousands and even hundreds of thousands of abandoned mine exists today in United States and every year thousands of people visit these mines, putting themselves at risk (Belwood, Jacqueline, & Rachel, 1991). Scanning of underground workings using a remotely controlled instruments such as a drone, could be an important new technology to assess the safety and environmental risks of both active and abandoned mines.

Geomechanics is the study of the mechanical behavior of rock and rock masses (Hoek, 1966). Geomechanics can also be defined as the study of deformation of soil and rock in response to stress, heat, erosion and other environmental factors that changes over time (Cook, 2015). Geotechnical engineering is the engineering discipline in civil, mining and petroleum engineering related to the study of behavior of earth materials for natural and manmade structures. Geomechanics is sub divided into rock mechanics and soil mechanics and geotechnical engineering uses principles of rock mechanics and soil mechanics to investigate surface and subsurface conditions, to determine the physical, mechanical and chemical properties of materials and to evaluate the stability of structures that involves geomaterials in some way.

Geomechanics was developed late in the history of mining. A series of a catastrophic incident in the 1950s and 1960s in France and South Africa led the mining industry to realize that the ability to engineer large structures is not sufficient (Bawden, 2015). The mining field advanced tremendously after this period, as did the field of geomechanics. A major contribution to the field of geomechanics was given by Dr. Karl Terzaghi who was considered the father of modern geomechanics for giving a clear definition of rocks with different structures and their different implications for engineering.

Lauffer in 1958 introduced the concept of standing time and pointed out that standing time for an unsupported excavation can be directly related to the quality of the rock mass of the excavation span. Deere in 1964 introduced the rock mass quality designation (RQD), at the time a more quantitative method to evaluate rock mass quality from standard cores. The first comprehensive rock mass classification systems were developed in the 1970s (Barton — Q-system (1974); Bieniawski -Rock Mass Rating (RMR) system (1973; 1976)). The most recent rock mass classification system to achieve wide acceptance is the geological strength index (GSI) (Hoek et al. 1995).

Both the surveying of large areas of land and the geotechnical monitoring of mining slopes in the mining industry, have a long history and evolution. After the invention of the airplane in 1903, the first aerial photographs from airplanes was conducted in 1908, primarily for the purposes of mapping and surveying (Oliver Homes, Aerometrex, 2012). 3D laser scanning was developed in the 1950's to scan and create detailed three-dimensional maps of various object (Ebrahim, 2016).the laser technology in scanners was continually improved, and by 1985, laser scanner with compact and efficient lasers were being developed. At the same time, the ability of computers and computer software to view and manipulate the output from laser scanners was improving at a rapid pace.

Around the 1980s, contact probes were developed which generate precise models but were slow. With the advent of the optical technology, new technologies for scanning were developed, including the point, area and stripe technologies. Cyberware was the first company which developed scanner that captures the color of the object as well as the 3D topography. In 1994, REPLICA introduced a 3D scanner that was fast and accurate and it marks a very serious evolution in the laser scanning world. In 1996, the dominant method for 3D scanning was done by using an operated arm and a stripe 3D scanner. This was the fastest and most flexible system at that time and the world's first reality capture system (Ebrahim, 2016).

The Drone technology has been continuously developing for many centuries with exponential growth seen in the last ten years. Drones are also known as Unmanned Aerial Vehicle (UAV) or Unmanned Aircraft Systems (UAS). UAVs can be defined as an aircraft without a human pilot or passengers. It can be operated remotely by a human operator or autonomously by using inbuilt computer system, however radio waves are mostly used to control drones (Kardasz & Doskocz, 2016).

Drones are equipped with sensors, motors, propellers, cameras and GPS systems. The power of a drone comes from the battery which is attached to the body and is mostly detachable. Initially, drones were used by the military as an anti-aircraft device for gathering intelligence information. But with the evolution of cheaper, smaller and efficient technologies, anyone can now afford to use a drone either to support their business or for recreational purposes. Part 107 of the Federal Aviation Administration (FAA) deals with Small Unmanned Aircraft Systems.

The most important advantage that a drone gives to its user is its light weight and quick preparation time for the flight. With its lightness, the drone can be carried anywhere, and the smallest size drones can even fit in a back-pack. Also, drones can be commissioned and prepared for a flight within a few minutes. Drones don't have a specific size but according to the FAA Part 107, small unmanned aircraft means an aircraft whose weight is less than 55 pounds on takeoff and this weight includes everything on board or otherwise attached to the aircraft. Normally a drone is equipped with two systems, one for the movement and another for the control of the drone (Kardasz & Doskocz, 2016). Drones can be broadly divided into 5 different types depending on the number of arms and motors:

1. Bicopters – Two engines
2. Tricopters- Three engines
3. Quadcopters- Four engines

4. Hexacopters- Six engines
5. Octocopters- Eight engines

Apart from the above classification which depends on the structure of a drone, it can also be classified according to the need (Kabir & Rahman, 2017). This classification includes use of a drone for Research and Development purpose, Emergency, Infrastructure Monitoring and Inspection, Earth Science, Environment and Defense and Security. In addition to above classification, a further classification of the drone can be done depending on different characteristics like Weight, Endurance and Range, Maximum Altitude, Wing Loading, Engine type and Power/Thrust Loading.

According to the FAA, there are different rules for flying drones with different purposes. This purpose includes recreational or commercial use. The drone registration has to be done with the FAA regardless of the use of the drone which costs only $5 per drone and is valid for 3 years. The UAV has to be operated within 400feet of height when in uncontrolled airspace and should never leave line-of-sight, meaning the drone operator must operate the drone using his own eyes, which includes utilizing contacts and binoculars to ensure the operator can see the drone at all times. The drone should never be operated close to another aircraft, or over groups of people, public events, or emergency response efforts.

Using the drone for a recreational purpose doesn’t require a pilot’s license however. Using the drone for commercial purposes does require that the operator possess an FAA certified drone pilot license, which requires passing a test to obtain one. One main reason for the sudden success and popularity of the drone is its pricing. The current low price of drones is favoring its use in a variety of industries and allowing people and companies to afford and utilize the full power of a drone. The growth of the drone also comes from technical advances that occurred from some initial early adapters such as military and associated companies (Panda Security, 2018).

Drones were initially developed for military purposes, and are now providing benefit to thousands of companies. Today the drone has important applications in the Civil and Mining Industries in the form of small quadcopters and octocopters which can be used to keep a track of inventory or to perform surveying of large lands or for security purposes. UAVs are used today for wide range of functions such as monitoring of climate change and delivering goods and carrying out search operations after natural disasters and for filming and photography. The list of the use of drone is unlimited and is growing day by day. UAV is also an increasingly important air power component for more than 80 countries today. American armed forces alone have a fleet of 11,000 drones today.

Until very recently the public perception about drones might be associated with the military use, even though today the drone activity is primarily non-military. The following timeline will provide a brief history of the drone over the past 100 years (Ebrahim, 2016).

1915-1920

The first pilotless aircraft was used in 1916 by the U.S Army to drop torpedoes during the war. The aircraft was flown using gyroscopic controls. Also, in 1910, the U.S. used bomb-filled balloons during the Spanish-American war.

1930-1945

In 1930, the U.S. Navy started experimenting with aircraft under radio control, the Curtiss N2C-2. Another aircraft called Queen-Bee was simultaneously developed by the British in 1935. During World War II, the U.S. produced around 15,000 drones for the army.

1980-1989

Although the United States was able to achieve mass production of drones for the military, drones were not considered reliable until 1982 when Israel forces used drones to gain victory over the Syrian Air Force. After this, the U.S started production of Pioneer drones for their fleet operation which further led to the development of RQ2 in 1986.

1990-2010

Smaller versions of drones were introduced in 1990, including the famous Predator drone that was used in 2000 to search for Osama Bin Laden in Afghanistan. In the following years surveillance drones were developed by American Technology Companies.

2010-2017

In 2014 Amazon surprised everyone with an idea to deliver consumer goods with the help of drones, as shown in figure 1. In addition, drones become popular in photography and videography.

The growing trend of drones was a result of the merger of radio-controlled aircrafts and smartphones. In 2014, the U.S. Military drone budget was $23.9Bn for 5 years.

The mining industry is continuously looking for innovative and efficient technologies to help improve the productivity of their mining sites and to increase the safety of mine personnel. Companies that give a high priority to environmental sustainability as well as cultural and community responsibility are the ones that will achieve a higher success rate. The mining industry has gone beyond traditional mining methods and are now utilizing modern tools and technologies, conducting innovative research, and developing futuristic equipment including autonomous vehicles, automated tunnel borers, and automated 3D mapping techniques.

Figure 1 The above picture shows the drone system launched by Amazon for delivery of good using a drone (Source: Amazon.com)

Unmanned Aerial Vehicles (UAVs) are an important part of the future for the mining industry. Figure 2 shows a drone in action at the Rio Tinto Kennecott mine in Utah. The drone is helping the Kennecott operation to identify safety risk which includes the identification of rock movement and signs of cracks (Mining.com, 2017).

The use of UAVs is one of the new innovative technologies to help mining companies drastically improve operational efficiency. The following are the benefits of the use of drones in the mining industry:

1. **Monitoring** – The first and foremost priority of the mining industry is safety, and various kinds of monitoring play a major role on increasing mine safety. Geotechnical monitoring by drones is an important new type of monitoring, and cold include remote monitoring of mining pillars and stopes, continuous monitoring of slopes and highwalls, and the use of point cloud and image processing programs to determine rock mass movement and predict failure (Sweeney, 2015). Geotechnical monitoring with drones could be particularly important in the underground environment, where traditional monitoring has serious access and safety issues.

Figure 2 A drone in work at Kennecott operation in Utah (Source: Mining.com)

2. **Cost Efficiency** - In the past, measurements of geostructures such as stockpiles or leach pads requires a team of surveyors to go to the field with surveying equipment. That practice is labor intensive and require a lot of time along with a significant amount of error. The use of drones as a surveying tool requires good planning but optimizes the use of personnel and results can be generated in real time with great precision, resulting in cost savings.

3. **Development and Resource Replacement** - By using a combination of UAV's and remote sensors, mines can increase productivity and optimize the use of equipment and manpower. For example, comprehensive land surveying can create three-dimensional contour maps to determine the locations of geostructures as well as the location of buildings and other

assets. Utilizing unmanned aerial vehicles can potentially be more cost-effective compared to tripod based new technologies such as GPS, total station and LiDAR surveys.

4. **Safety and Security** – Utilizing drones helps prevent unnecessary accidents by detecting dangerous risks and identifying new sources of danger. With advanced remote sensors and continuous monitoring methods, drones help ensure continuous monitoring of increasingly complex mining projects. A drone can perform continuous monitoring of processing plants and other buildings for safety hazards, and it can monitor geostructures for unstable rock movement. It can also assist with emergency escape and rescue missions.

The use of drones has become more attractive in the mining industry in recent years as falling commodity prices have forced mining companies to seek ways to increase productivity. The deployment of drones throughout the mining industry is already seeing a rapid increase from year to year. Drones provide a birds-eye view that map out areas more efficiently than by a surveyor manually. Unmanned data flights are allowing mining companies to survey huge areas at a cheaper price, less time and with stronger safety margins. Companies no longer must deploy ground vehicles into rough areas, often with inaccessible and dangerous terrain. So far, the use of the drones has been limited to operations such as stockpile management, haulage optimization, tailing dams, security, emergency response and geotechnical monitoring of highwall and slopes.

With tough competition in the market to produce more commodities, there is a parallel need of extracting more mineral resources from a site using techniques such as steepening the slopes of the pit. The slope steepening can produce more ore with less waste, but at the possible risk of increasing slope instability. Optimizing a slope design is possible through advances such as drones that allow more data on rock characterization and rock movement to be collected. In the bigger picture, drones allow all aspects of mine optimization and mine safety to be improved.

The idea behind this research is to use drones in an underground environment for geotechnical monitoring. This research includes reviewing previous work that has been conducted on this subject, as well as conducting new research on underground geotechnical monitoring using drones. There are many aspects to the new research described in this thesis, including optimizing the procedures for taking video images underground, understanding the accuracy and error of point clouds generated from the underground video, and developing new ways for extracting geotechnical information from the point clouds that include rock mass characterization and rock mass movement.

1.1 POINT CLOUD

A point cloud is a set of data points in three-dimensional space. It is one of the fundamental types of geospatial data, the others being vector and raster. Point clouds are generated either by ground based or airborne LiDAR, or by using a camera to capture images and using Photogrammetry. LiDAR and Photogrammetry are now common remote sensing methods employed to measure the 3D coordinates of surfaces either by continuously emitting rays of lights and collecting them which give the location of the point in the space or by capturing several images and combining those images to get the point cloud. Point clouds have proven to be very useful in the mining and civil industries.

Based on advancements in point cloud technologies, point clouds can be constructed automatically from video images using the Semi Global Matching (SGM) and Structure from Motion methods (SfM). The SGM method is used to find the same pixel locations in a pair of different images by using the intrinsic and extrinsic orientations of the camera (Hirschmüller, 2002). The SfM method is the technique to produce three-dimensional structure from two dimensional images. The most important factor while capturing camera images or using scanners is viewing the scene of interest from many locations and angles. (Grzegorz Ciepka, 3Deling, 2016). The field of view is the area within the reach of the sensor in which an object can be detected. If an object cannot be view from the position of the scanner it cannot be imaged and converted into point cloud. Apart from the object being outside field of view, sometimes a scanner or camera will not be able to detect the object if the reflected light is too weak (LIVOX).

Open pit and underground mines of almost every size around the world are using point cloud data on a regular basis either for surveying, planning or geotechnical study. Over the past few decades, point cloud acquisition devices have finally become affordable, and also lighter, smaller and easier to operate. Also, with the rapid growth in point cloud technologies, open pit and underground mines are regularly using point clouds for rock mass characterization (Lyons-Baral & Kemeny, 2016).

Point clouds come in different forms. The simplest form consists of the location (X, Y, Z) of each point in 3D space. Lidar scanners also produce an intensity value for each point based on the strength of the return laser signal (X, Y, Z, I). (Wagg & Manager, 2012). A color point cloud is the usual output of photogrammetry and consists of a 3D position and color of each point (X, Y, Z, R, G, B). Lidar scanners can also produce color point clouds by utilizing a built-in camera in addition to a laser unit. Important properties of point clouds include the point cloud density (spacing between points) and the point cloud resolution (accuracy of the X, Y, Z points).

LiDAR scanners capture the location of a laser return pulse in the form of range angle and time. These values are then converted to 3D locations such as latitude, longitude and altitude. In systems that are moving as they collect the data (airborne Lidar for example), location values are collected using the onboard GNSS (Global Navigation Satellite System). In addition, the IMU (Inertial Measuring Unit) captures the roll, pitch and heading which is integrated with GNSS. The integration of the data is mostly automated. Point clouds generated from overlapping digital images utilize photogrammetry software such as Pix4D Mapper, Drone Deploy, Autodesk, Agisoft, and PhotoScan.

Storing point cloud data can be a major issue and can involve terrabytes of data for a single site. As point clouds become more popular, the data storage needs are growing faster than the database management systems can handle. As a result, data is often stored in compressed formats instead of simple data structures such as the ASCII file format (Lemmens, 2014).

Following are the major uses of point clouds in the Mining Industry:

Monitoring: Monitoring changes occurring in point clouds taken of the same scene but at different periods of time is known as change detection. Change detection from point clouds has many advantages over traditional methods of monitoring including safety, speed, and reliability. The combined use of surface and underground point clouds can provide a precise 3D model of bedding planes, faults, fractures, mining pillars, conduits, sinkholes, etc. Changes in rock mass conditions over time can occur due to blasting, excavations and hydrological changes. UAVs can scan large areas within minutes, and when repeated at intervals of time, can produce important monitoring results. A common technique of change detection is to precisely align two-point clouds of the same scene and then perform “subtraction”. This provides information on movement in the direction of the subtraction. The subtraction can be point to point, mesh to mesh, or point to mesh (Palma, Cignoni, Boubekeur, & Scopigno, 2016). Using this technique, rock mass deformation can be recognized and mitigated. In surface mining, change detection can be used to monitor slopes, stock piles, leach piles, and tailings. In underground mining, change detection can monitor stopes, drifts, large excavations for crushers, and many other types of underground excavations.

Blasting: UAV's can be used to capture high resolution low height images which can be used to generate high density point clouds. Point clouds can be used to assist the charging of the holes and can help with post blasting inspection. It can also be used to monitor before and after scaling that is needed after a blast. The 3D model combined with borehole data can be used to identify the areas of weaknesses and confinement.

Rock mass characterization and properties: Point clouds provide a very valuable tool for geological and geotechnical data collection, processing, analysis and interpretation. Kemeny and Kim (2009) demonstrate how point clouds can be used for road cut and outcrop slope stability analysis and discontinuum modelling. Point clouds allow the remote acquisition of data to increase safety. Point clouds of exposed rock faces can be used to extract information on fracture orientation, roughness, persistence, and spacing. Rock mass quality indicators such as the Rock Quality Designation (RQD) and the Geologic Strength Index (GSI) can also be determined with point cloud data. All this information can then be utilized along with stereonet and slope stability software to determine the factor of safety and probability of failure for rock engineering design.

1.2 INNOVATION

The focus of the thesis describes on this thesis is the use of drones for underground geotechnical analysis. This research is of importance because drones have not been utilized on a wide scale in underground mining for monitoring and surveying. Underground mines are still using traditional mining monitoring methods such as laser scanning, CMS and borehole extensometers for tracking the movement of rock. These processes are time-consuming, costly and carry some safety risk. This research innovatively investigates underground drone photogrammetry by using a combination of drone and a high-resolution camera. In a few of the test flights, this research shows how putting the drone in auto mode captures better quality pictures then using a manual method with fixed ISO and focal length.

This research demonstrates that the use of drones in underground can produce similar results to those of LIDAR and other scanning tools. The test flights were performed with the use of a Phantom 4 drone at the 100 feet level at the University of Arizona SX Mine, and the research using this unique University facility represents the conditions that would be expected in actual underground mining operations. Most importantly, underground mines generally lack GPS and adequate lightning, which represents two major challenges for successful drone operations. The Phantom 4 drone has never officially been used in an underground mine for photogrammetry purpose. There was a total of 18 test flights carried out at different locations including the San Xavier Mine, Pepper Sauce Cave and the Rock Mechanics Lab at the University of Arizona. All these tests were used to increase knowledge and develop techniques for deploying drones in underground for geotechnical purposes.

This research is also unique in that it directly compares underground drone point cloud data with that of underground LIDAR, for both the geotechnical operations of change detection and rock mass characterization. This thesis demonstrates that a high-density point cloud can be generated from a drone in an underground space in less time and more accuracy than conventional methods. This thesis shows how innovation can be used to develop and utilize a scanning system that is cheap, modern and safe. The innovative approach while performing research includes the use of simple caving lights mounted on a drone to eliminate lighting issues and to capture sharp images. This innovation will save mining companies thousands of dollars that they currently spend to purchase costly scanning systems.

1.3 SCOPE OF THE THESIS

This thesis consists six different chapters. Chapter 1 includes the introduction to the thesis, which includes the history of the mining, the importance of geomechanics in the mining industry and the use of geotechnical engineering in the evaluation of surface and subsurface conditions. It contains a history and evolution of scanning equipment, how drone technology came into the mining industry, the reasons behind their success. It explains different types of drones based on various criteria and the history of drones to date. Section 1.1 discusses what a point cloud is, its properties and how they are generated using aerial and terrestrial techniques. It also discusses the benefits of the point cloud in different aspects of the mining industry, such as monitoring, blasting, and rock mass characterization. Section 1.2 explains why this research topic is unique and innovative.

Chapter 2 defines the background of this thesis, including an explanation of the characteristics of the point cloud, such as point spacing, point density and the formation of voids after processing point cloud data. Section 2.2 describes the traditional ways to acquire point cloud data by using LIDAR scanning and the Photogrammetry method. Chapter 2.3 explains the differences between the point cloud data generated by the LIDAR scanner and Photogrammetry techniques based on the accuracy of the point cloud, data acquisition, processing, and efficiency. Section 2.4 is subdivided into section 2.4.1 which describes the method to obtain point clouds from the scanner, while Section 2.4.2 describes the means to generate a point cloud from drones on the surface and in an underground mine. Section 2.4 also explains a step by step process to capture and process point cloud data using a drone and PIX4D software.

Chapter 3 explains the equipment that was used to perform the research for this thesis and the methodology adopted to carry out the research, giving justification for the selection of appropriate equipment over other equipment. Section 3.3 describes the challenges faced while carrying out this research and the steps to be taken to solve those challenges. Chapter 3.4 describes the selection of the San Xavier Mining Laboratory for the study and the benefits it provides to the thesis and the University.

Chapter 4 describes the complete details of all the test flights performed during the course of eight months. It describes all the experiments performed at the SX Mine, both on the surface and underground, with the rationale for performing each test and other details like how many images were captured and how many points were generated.

Chapter 5 discusses the result of the experiments performed and analyzes those results. At the end of this chapter there is a good understanding of the difference between point clouds generated from drones and LIDAR scanners. And why the drone point clouds are enough for geotechnical purposes.

Chapter 6 is the final chapter of the thesis, giving conclusions and recommendations for future work.

2. BACKGROUND

This section of the thesis will discuss the different characteristics of the point cloud like density and point spacing and the traditional ways to generate point clouds by utilizing the LIDAR and photogrammetry methods. It also discusses the difference between point clouds generated by both methods in terms of accuracy, method of data acquisition**,** processing and efficiency. This section also describes the methods to generate point cloud data by using laser scanners and drones both on a surface mine and an underground mine.

2.1 CHARACTERISTICS OF POINT CLOUD

A point cloud is a collection of data that represents a 3D shape and different feature of the object. Each point has its own set of X, Y and Z coordinates, and R, G and B color codes. Point clouds are generated by 3D scanners, which measure the surface of the object and generate many points by scanning the external surfaces of object. As the output of 3D scanning processes, point clouds are used for many purposes such as monitoring slopes, surveying structures such as stockpiles, creating 3D models for manufactured parts, and for applications in visualization, animation, rendering and mass customization.

Point density and point spacing are very crucial properties of point cloud. Point density is defined as the number of points in a unit area (points per square meter); however, point spacing is defined as the distance between two close points in a point cloud set. In an evenly distributed point cloud, the point spacing is the square root of average area per point (the area of polygon divided by the number of points it contains). Small point spacing suggests that there are more points in an area and, hence, that the point cloud is dense. A high-density point cloud can represent an object more clearly than a sparse point cloud.

One phenomenon that happens while producing point cloud is the creation of voids. These are gaps in the point cloud data that have no points and can occur because of the surface absorbance, scattering or reflection of LiDAR pulses back from the surface (Heidemann, 2018). Sometimes the scanner can be at fault because of instrument anomalies, but usually it is the fault of the scanning method. Data voids can occur in dense vegetation, due to the plants not being penetrated by LiDAR beam, or it can happen due to the presence of fog or high wind or dust, or the presence of water bodies that absorb LiDAR beam (Dharmapuri, LIDAR Magazine, 2018). In photogrammetric data, voids can occur due to insufficient light for the sensor to capture data and this is what happens while performing test flight 6, which is further discussed in detail in section 4. The environment while collecting data should be fog- and dust- free. Snowy areas should be also avoided for scanning purposes because the scanner and cameras are unable to detect any similarity between data sets (everything being white), thus creating a void. Data should always be tied to a georeferenced datum and, with advancements in technology, datum is very precise and accurate.

Another aspect of the point cloud is the presence of noise. Noise is undesirable points present in the point cloud that are irrelevant for processing and can occur because of improper planning or unfavorable conditions. Noise in point clouds increases processing time. With the software currently in the market, however, noise can be reduced automatically or filtered out manually. Over the course of time, many filtering techniques such as Filin and Pfeifer have been developed to help with noise removal (Lemmens, 2014).

Point clouds are also used for 3D surface reconstruction for further visualization and analysis. The generation of polygon models after the restoration of point cloud data depicts the object accurately with correct measurements and optimal surface descriptions. This model can be used to analyze surfaces for cracks and fractures, and to perform geomechanical analysis.

With the advancement of mining software, it is now possible to process images from drones and create a point cloud within an hour. Modern scanners can produce a massive point cloud of significant structures and rock masses within a few millimeters of precision. However, the density of a point cloud depends on several parameters from both the operational conditions and the specifications of the project, such as the resolution and quality of the scanner stations and the purpose of scans. For this research, the focus is the monitoring of the rock mass properties to analyze any discontinuity associated with the rock mass.

CC is the open source software used to extract information from a dense point cloud, and Pix4D is the processing software to obtain a point cloud from the images. Since Pix4D is a cloud-based processing platform, the point cloud is a complete stitched form and dense and hence no further registration required. However, with the desktop-based version of Pix4D, there is an option to select the density needed. The denser the point cloud, the more processing time it takes.

2.2 TRADITIONAL WAYS TO GET POINT CLOUD

Based on the type of scanning process, scanning can be carried out by LiDAR scanner or Photogrammetry. LiDAR (Light Detection and Ranging) is a remote sensing method that uses light in the form of a laser pulse to measure variable distances between object and scanner. Laser scanning can be divided into three types: terrestrial, aerial and mobile. Mobile scanning is the latest addition to the list. Photogrammetry method uses images to generate point cloud data and can be mounted on a tripod or on an aircraft or drone.

In early days, a point cloud was generated by using active remote sensing equipment such as radar, laser scanners, or Cavity Monitoring Systems (CMS), using an aerial or terrestrial platform. In terrestrial scanning, scanners are mounted on a tripod and placed on the ground with scanner pointing towards the object. In the CMS method, the scanner is mounted on a boom and extended inside a mining stope for monitoring. In case of aerial scanning, a laser scanner is mounted on an aircraft pointed vertically downward.

A LiDAR instrument consists of a laser, a scanner, and a GPS receiver. Based on the area of usage, two types of LiDAR are commonly used: topographic and bathymetric. Topographic LiDAR uses an infrared laser to map the terrain, while bathymetric LiDAR uses water penetrating green light to measure seafloor and beds. When an airborne LiDAR laser is pointed at an object, it sends a continuous beam of light; the light is reflected and collected by the scanner. A ray of continuous laser lights emits the beam, and the scanner keeps on spinning around the vertical axis to move the beam up and down in a different direction. When the beam hits the object, some of the energy of the beam is absorbed, and some is reflected. The reflected beam is received by a scanner. A sensor records this light to measure a range. At the same time, with the help of GPS and an integrated IMU unit present in the scanner, it marks the X, Y and Z location along the angle of the reflection. The resulting scan is a set of 3D coordinate measurements. Each point has a set of latitude, longitude and height and some color features that resemble the original object. This accurate representation of the scene is known as a point cloud.

Registration of a point cloud is a process to stitch all the points from different scans in one cloud. LiDAR is used to generate a 3D model of the surfaces, stockpiles and large mining areas. It is extensively used to monitor slopes in open pit and underground mines.

Digital Photogrammetry was first proposed by Ian Dorman in 1984 to map the topography of terrain using satellite imagery (Kos, Tompkinson, Conforti, Lunghi, & Naenni, 2014). Photogrammetry is based on perspective geometry. It is a technique of taking multiple overlapping images and deriving measurement from the photos to create point cloud and 3D models. Original image. An example of how Photogrammetry works is shown in Figure 4, demonstrating the mounting of the camera beneath the aircraft. Photogrammetry takes the concept of the position of the camera as it moves in 3D space to find the location of each pixel in different images and then estimating the X, Y and Z coordinate of the different points.

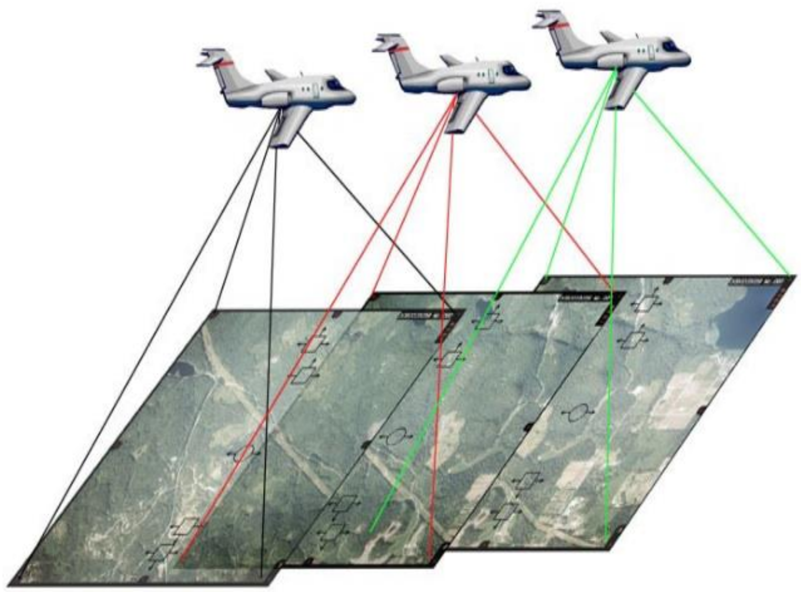


Figure 3 The above image demonstrates the basic principle of photogrammetry by mounting a camera on an airplane point towards ground. A series of overlapped images taken by camera is used to generate point cloud by using Structure from Motion (Sfm) method (Source: GIS Resources)

The technique being used for Photogrammetry to get the point cloud is known as Structure from Motion (SFM). Knowing the position of the image allows us to calculate a 3D vector from the image point through the perspective center. With two or more overlapping images, a 3D vector can be drawn to calculate the actual position of the point in the scene. These methods can be deployed from airplanes, unpiloted aerial systems (UAS or drones), tripods, land vehicles or even in a mobile backpack. RADAR, Total Station-Prism and other remote sensing systems also offer exact point clouds.

In Terrestrial and Close-range Photogrammetry, the camera is located on the ground, and handheld, tripod or pole mounted. Usually, this type of Photogrammetry is non-topographic: the outputs are not topographic products like terrain models or topographic maps. Instead, they are drawings, 3D models, measurements, or point clouds. Everyday cameras are used to model and measure buildings, engineering structures, forensic and accident scenes, mines, earthworks, stockpiles, archaeological artifacts, film sets, etc. In the computer vision community, this type of Photogrammetry is sometimes called Image-Based Modeling.

Over the past few decades, the use of surveying devices has become more affordable as the price of point cloud acquisition devices has dropped significantly. Now the surveying devices are smaller, lighter and easier to operate, and the acquisition and processing of data have become faster and easier.

2.4 GENERATION OF POINT CLOUD FROM DRONES

2.4.1 SURFACE POINT CLOUD FROM DRONES

Research by a group of engineers in Rochefort Cave, Belgium, was made to compare the work flow and accuracy between LiDAR scanning and drone Photogrammetry. This study considered data acquisition and processing, the quality of the resulting 3D point cloud, potential application areas related to geological topics (Watlet, Triantafyllou, Kaufmann, & Le Mouelic, 2016). The results suggest that LiDAR creates a higher density point cloud with more precision and accuracy compared to photogrammetry. However, the 3D data produced by photogrammetry provided more visual information about scanned objects that can be helpful in further data analysis. LiDAR scanning was found to be generally costlier for periodic surveys compared to UAV. UAV processing is considerably improved in terms of cost and ease of use compared with 10 years ago. LiDAR point clouds are obtained by using scanners mounted from airplanes pointed directly toward an object or mounted on a tripod stand. Generation of point clouds from UAVs requires a few simple steps:

1. Flight and image acquisition planning: PIX4D software has two different modes for image capture: auto and manual. PIX4D and all the major processing software provide free drone mapping applications that can be installed on computers, tablets and smartphones. This application helps to select the location of the scan on the map and helps to capture the picture. In auto mode, the software itself optimizes the number of pictures required to process, in order to generate the best results. It also offers different options, such as fixed camera angle, the percentage of overlap required and the speed of drone. In this approach, the drone stops itself at a fixed height and hovers around the object to capture optimal pictures with enough overlap. Auto mode becomes impractical where the scanning area is complex, and the project need more detailed analysis. Figure 5 shows the screen capture of the flight planning in PIX4D software.

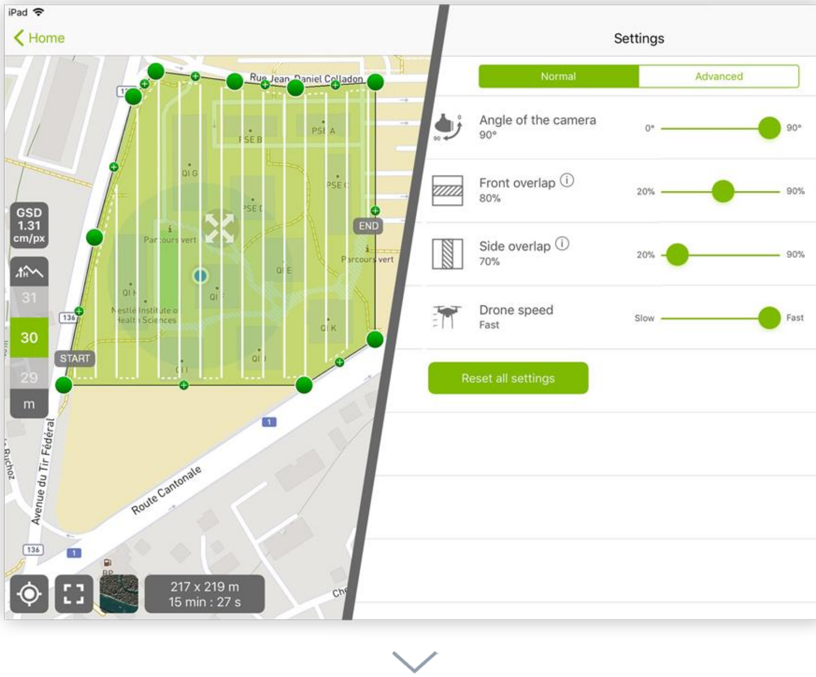


Figure 4 The first step of capturing image by using a drone for photogrammetry is setting up the path for the image capture. (Source: PIX4D support)

In manual mode, the number of acquired images depends on the skill and experience of the pilot. A fixed continuous interval shot can be engaged for better overlap between the images, and the pilot is also able to fly in more complex terrain conditions than in auto mode.

2. Image processing: After the acquisition of the picture from the drone, the next step is to process the picture in the PIX4D software. PIX4D software provides both cloud and desktop processing. The desktop mode offers a wide range of image processing options, while the cloud processing has does not have options. The drone is equipped with different types of sensors, such as IMUs, gyroscopes and barometers. These sensors record the elevation at which the image is captured with the help of GNSS/IMU systems and records the pitch, roll and yaw of the drone, corresponding to the position of the drone in the X, Y and Z axes.

The following steps navigate through the process of image processing using PIX4D software:

1.The first step is to create a folder for the project. Figure 7 shows the option to create a new project.

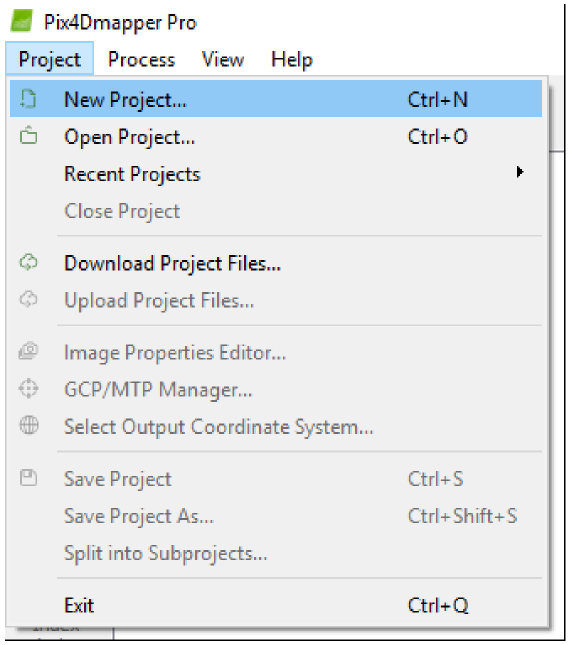


Figure 5 The menu option showing building a new project (Source: PIX4D support)

2. The next step is naming the project and selecting the folder where the project should be Located, as shown in Figure 8

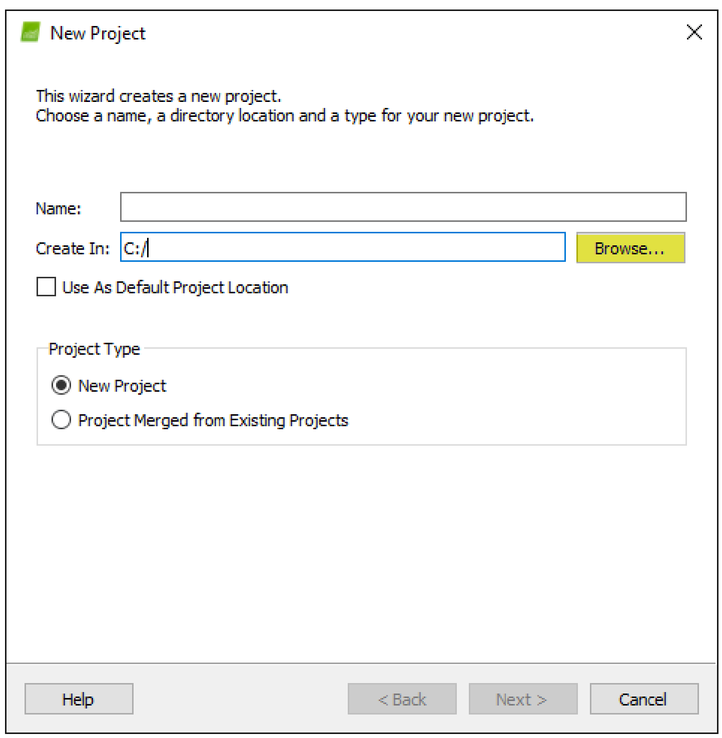


Figure 6 The option to put the name and location of the project (Source: PIX4D support)

3. Adding captured images to the project is the next step and can be seen in Figure 9. There is the option to add different types of images, such as RGB, drone, multispectral, thermal, fisheye, 360 degree, and camera rig images, as well as videos.

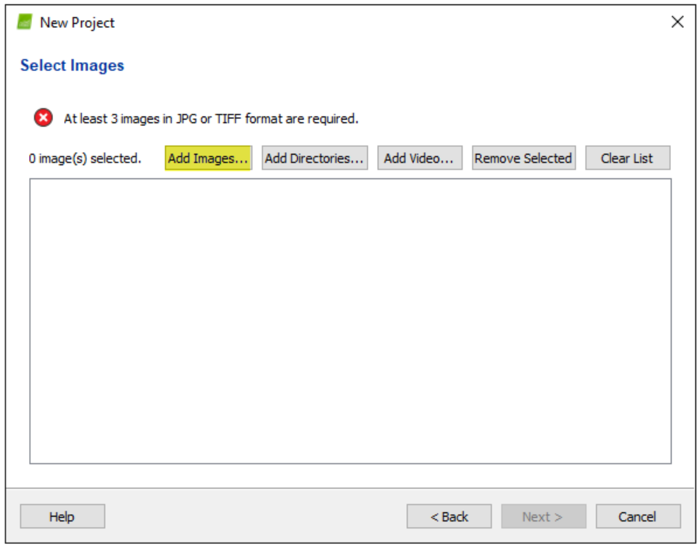


Figure 7 The option to add images for processing in the software. It gives an additional option to add video and the software itself can extract the image from the video. (Source: PIX4D support)

4. Next is the selecting of the output coordinate system and georeferencing, as shown in Figure 8. If the images have geolocation, by default, Auto Detected is selected, displaying the

corresponding UTM (Universal Transverse Mercator) zone of the image. If the image does not have a geolocation, by default, Arbitrary Coordinate System is detected.

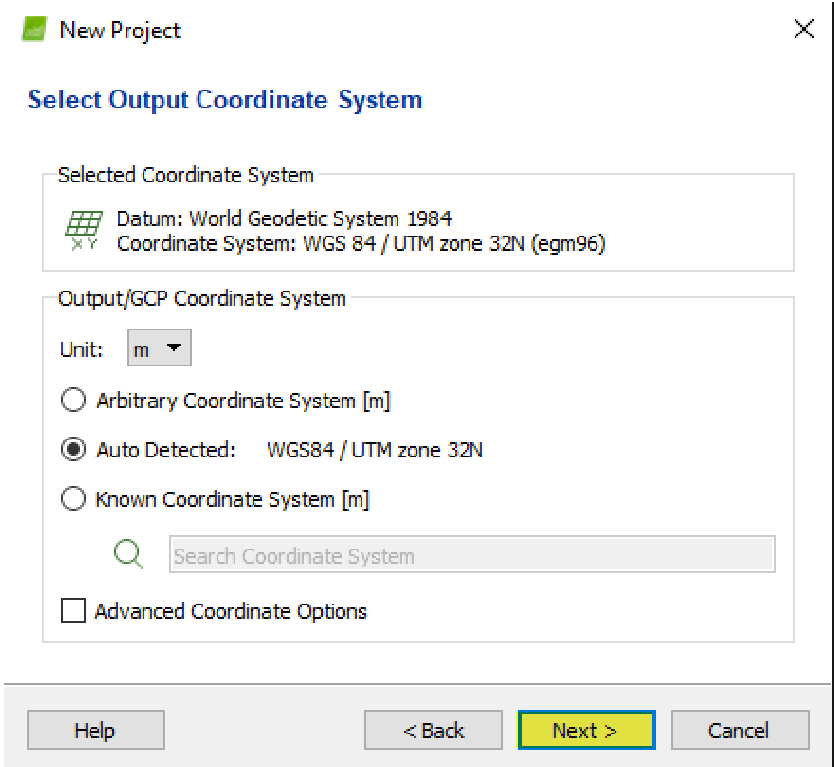


Figure 8 The option to select the output coordinate system (Source: PIX4D support)

5. Selecting the processing options is the next step and can be seen in Figure 9. The processing options include generating 3D maps (DSM and an Orthomosaic), 3D models (point cloud, 3D texture mesh), Ag Multispectral, 3D maps (Rapid/Low Res) and 3D Models (Rapid/Low Res). Apart from the output result, the software also provides a quality report that provides camera position, tie point positions, number of overlapping images, camera parameters, geolocation details and other processing details.

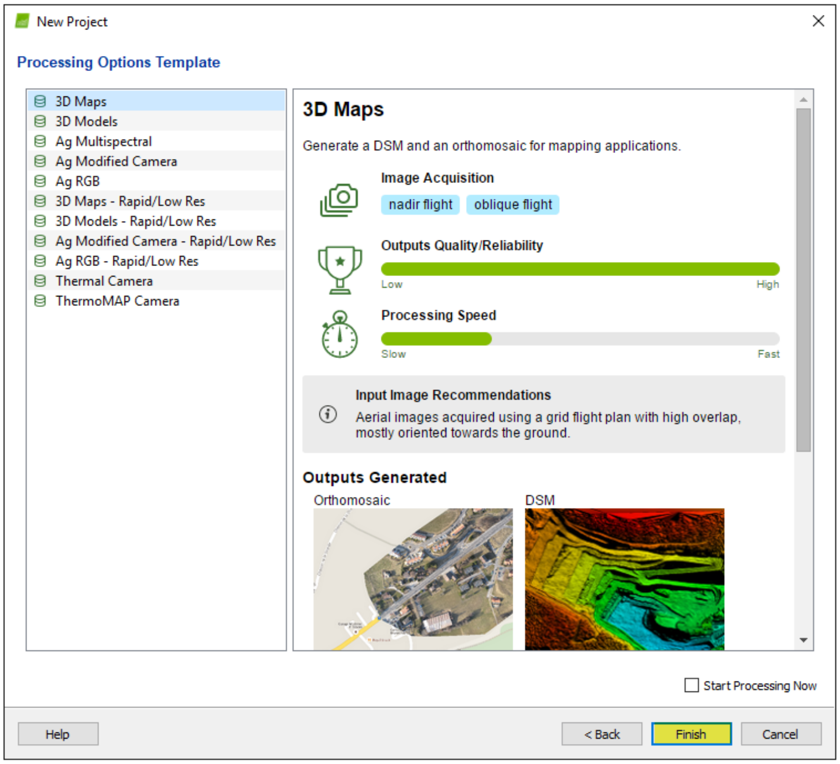


Figure 9 The different output options available with the software giving the engineer a wide range of options (Source: PIX4D support)

6. The above steps describe the process to setup and define the location of the project and selecting the processing template. Apart from the above options, the software also provides options

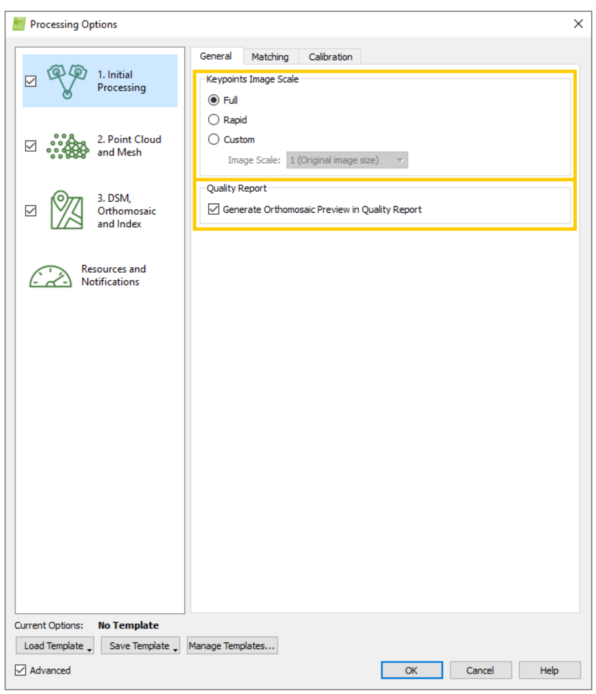


Figure 10 Initial processing option in PIX4D software

to optimize the output of the project. The four options include Initial Processing, Point Cloud and Mesh, SM, Orthomosaic and Index and Resource and notification. The Initial Processing option can be seen in the Figure 10. The Point Cloud and Mesh gives an option to select the scale of the image and the density of the point cloud and the format of the Point Cloud file after processing. It is always advisable to check the 'Merge Tiles into One File' because, when processing images, PIX4D generates several point cloud files and, if the box is not checked, it will create several point cloud files. Figure 11 shows the option for Point Cloud and Mesh..

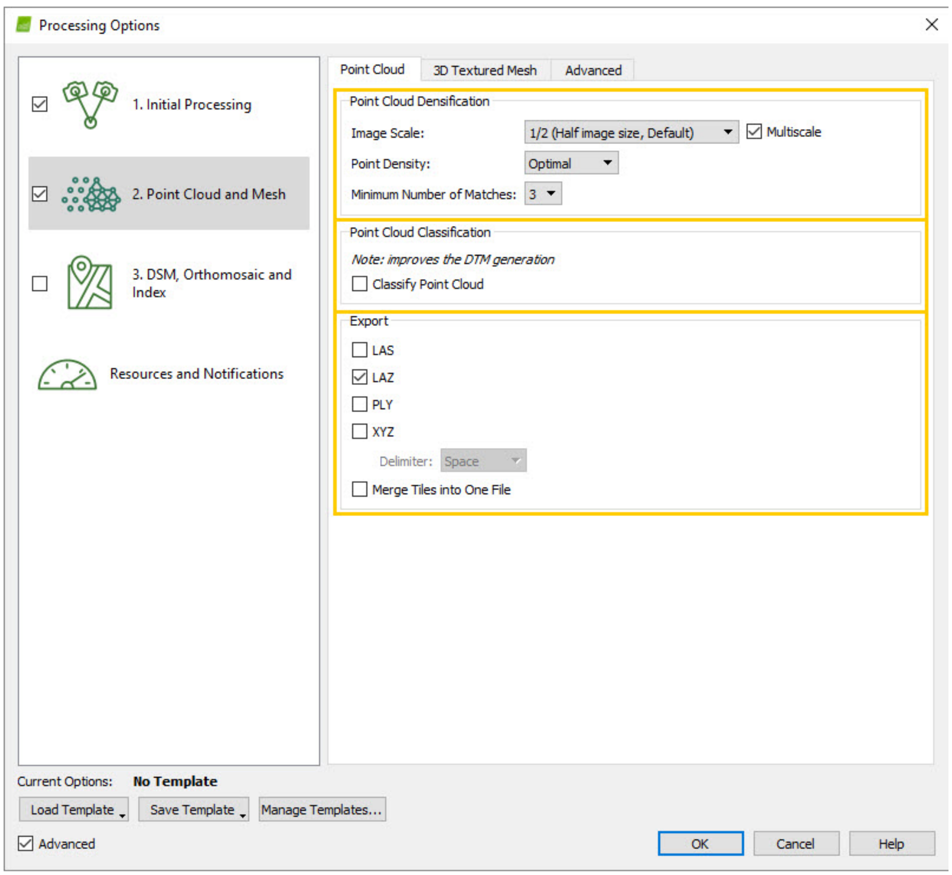


Figure 11 Options for changing the input to vary the output of the point cloud like density, image scale and the format of the output file

2.4.2 UNDERGROUND POINT CLOUD FROM DRONES

The generation of underground point cloud data sets by use of drone consists of the same process as on the surface, with the only difference lying in the process of acquisition of pictures. In the surface image capture, the process is automated, using flight pre-planning that optimizes the image capture process as the software knows the number of images to capture and processes those pictures in the PIX4D software to generate an optimum point cloud. In the case of an underground mine using a drone, this is not available as the pre-flight planning cannot be defined due to the undefined underground opening and structure.

After working with the stabilization and GPS problems, the drone has two options to generate a point cloud. For this research, most of the tests were performed on the surface during night time, considering it to be an ideal condition for the drone to fly. In this condition, which approximates the underground condition with drone stabilization, the drone has the option to capture either still images or video. The benefit of using PIX4D software for this research is that the software can convert the video into still images, allowing for more flexibility for the user. This is further explained in the methodology section. After the acquisition of the image, it can be uploaded in the PIX4D software and, following the steps mentioned above, the point cloud can be generated.

3. RESEARCH APPROACH

3.1 OUTLINE OF RESEARCH

The use of a drone in an underground mine for geotechnical monitoring can provide the mining industry with an efficient, safe, fast and cost-effective monitoring and surveying method. In this section the research approach and methodology towards this topic are discussed. This includes the selection of various equipment for underground geotechnical monitoring with drones, including the justification for using certain equipment compared with others. It also describes the challenges and how various field experiments were performed to overcome those challenges. It also describes the specific locations that were chosen to perform the experiments and the overall benefits of the field experiments.

3.2 EQUIPMENT

One of the primary outcomes of this research is determine the equipment and equipment parameters that provide safe and automated underground geotechnical monitoring using drones with monitoring results that are accurate, fast and cost-effective. The above criteria can only be fulfilled by using an autonomous drone system for monitoring. The word autonomous means that the system will be able to carry out unaccompanied data collection. This can be followed by processing and analysis which can be performed either manually or semi-automated. In this research we utilize an off-the-shelf drone and modify it to capture images and then perform photogrammetry to generate point cloud data. It is not a simple process to use a drone in an underground environment. Field trials need to be conducted, and procedures need to be developed based on iterative improvements and modifications. The challenges faced while using a drone in an underground space is elaborated in the upcoming section.

The challenges faced while performing this research is mostly associated with the compatibility of the drone in an underground mine. A normal drone that can hover and perform essential monitoring and inspection work on the surface cannot be used in an underground mine with the same level of flexibility. The two major problems that drones face in an underground mine are the lack of natural light and GPS unavailability. The presence of natural light on the surface makes photogrammetry much easier as the camera adjusts to the brightness of the sunlight and maintains an optimal picture quality to produce a dense point cloud. However, in an underground space where no natural light is present, the photogrammetry process becomes difficult and potentially less accurate as the camera must reduce the shutter speed to account for low light conditions. This can create blurry images which do not register as accurately as sharp images. The other problem faced by drones in an underground mine is GPS unavailability. In the absence of GPS in an underground mine, the drone finds it hard to balance itself and hold a constant position. To work out these two challenges in the research, the following equipment has been selected.

1. DJI Phantom 4

For this research purpose, the DJI Phantom 4 drone was selected. The features that supported the selection of this drone for the research are listed below.

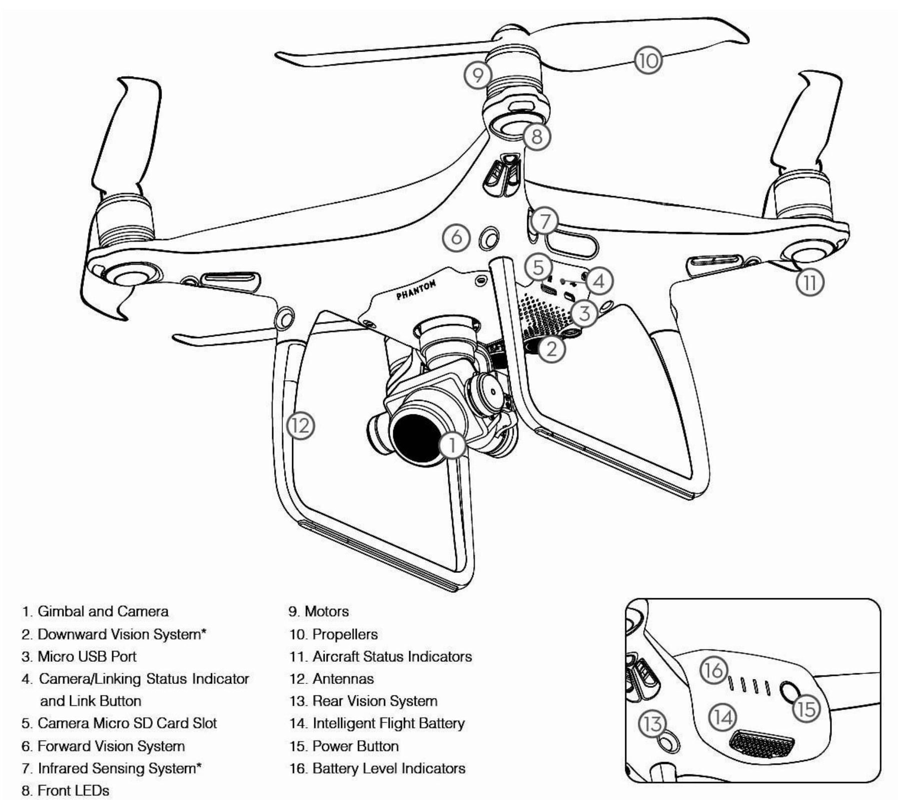


Figure 12 Different parts of the drone showing battery and camera gimbal

Autonomous Flight Functionality: The drone is equipped with autonomous flying modes for different scenarios, including object tracking modes, a pre-defined path flying mode, and even a "follow the terrain" mode. Coupled with the excellent obstacle avoidance systems, the DJI Phantom 4 can be used for a variety of surveying and monitoring purposes. These features were used to perform and validate a number of field tests to assess the accuracy of the measurement in an underground space compared with a surface space.

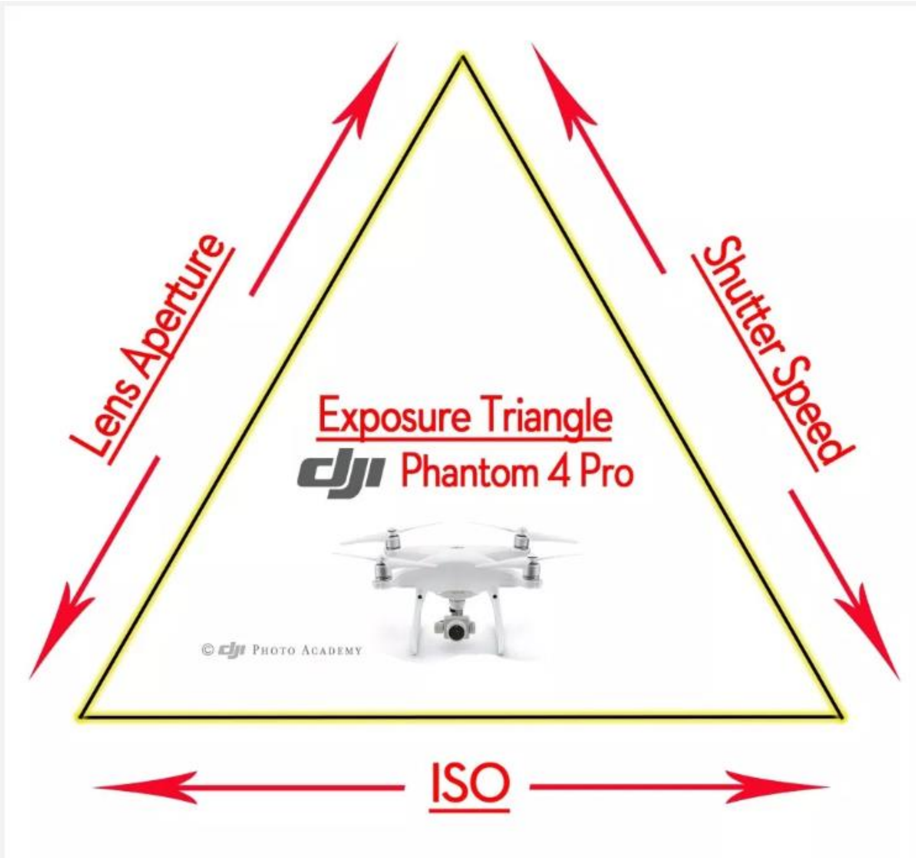
Obstacle Avoidance Sensor: The two most important features of the Phantom 4 that make it ideal for the mining industry are its Sensors and Camera. The Phantom 4 Pro has an advanced 5-direction obstacle avoidance system, unlike other drones with only forward/downward facing sensors. These sensors come into effect mostly when the drone is out of line-of-sight. These sensors on the forward and downward side also help the drone to maneuver for optimal landings. This greatly minimizes the risk of crashing when flying backward or to a side with limited visibility. Sensors always provide better control and stability when flying indoors.

Specs/Model	Phantom 4
Weight of Aircraft (Battery Included)	1380g
Max. Flight Speed	20m/s (Sport Mode)
Max. Ascent/Descent Speed	6m/s ascending (Sport Mode); 4m/s descending (Sport Mode)
Flight Time	Over 28 mins
Obstacle Sensing System	Yes. Effective range is 0.7 – 15m
Vision Positioning System	Yes. Effective range is 0-10m
Slow Motion Video Recording	Yes. Resolution: 1920*1080@120fps
Intelligent Flight Battery Capacity	5350 mAh

Figure 13 Technical specifications of the Phantom 4 drone showing flight time and weight of aircraft

The obstacle sensing range is 30 meters for the rear and the obstacle avoidance system range goes from 0.2m to 7m for side sensors, and the max speed for obstacle avoidance is 50 km/h (31 mph). The obstacle avoidance sensor works in all direction except upward. The drone avoids obstacles either by moving past them or stopping right at the obstacle. Narrow sensing is also a special feature of Phantom 4 as it let the pilot turn off the obstacle sensing and go closer to the object to capture more detail about it (Aerial Guide, 2018).

Camera: The drone boasts a large sensor almost four times as large as those in high-end smartphones. The DJI Phantom 4 Pro's camera is equipped with a 1-inch 20-megapixel sensor. This big sensor collects enough light to allow shooting bright pictures in dark settings and that is helpful while shooting for images in a dark underground space. DJI uses the **dreaded exposure triangle** for photography, as introduced by DJI and shown in figure 14 (Randy Braun, 2018). This triangle gives an idea on how to make a balance between lens aperture, shutter speed and ISO to get the best picture for photogrammetry.



The dreaded exposure triangle!

Figure 14 The Dreaded Exposure triangle shows the relation between lens aperture, shutter speed and ISO

This concept helps the photographer controls the balance between ISO, aperture and shutter speed. The three elements need to be in balance to capture a good picture with exposure. It has a mechanical shutter and manual focus system which helps in both day and night lightning. It also has a manually adjustable aperture from F2.8 – F11. This is really helpful while using manual mode and in low light conditions. The camera captures images in RAW and JPG mode giving an option to capture more information about the object, which can then be edited at a later point of time. The camera has a wide range of ISO from 100-6400 for video mode and 100-12800 for photo mode. Using a low ISO generates a high-quality image with minimal noise. The Phantom 4 has a 3-axis gimbal stabilization which ensures that the motion of the camera is stabilized even if the drone is going up and down, left and right or forward and backward. The camera also offers a variety of time intervals to auto capture images. This time interval includes 2, 3, 5,7,10,15,20,10 and 60 sec. This allows the pilot to focus more on the functioning of drone rather than image quality.

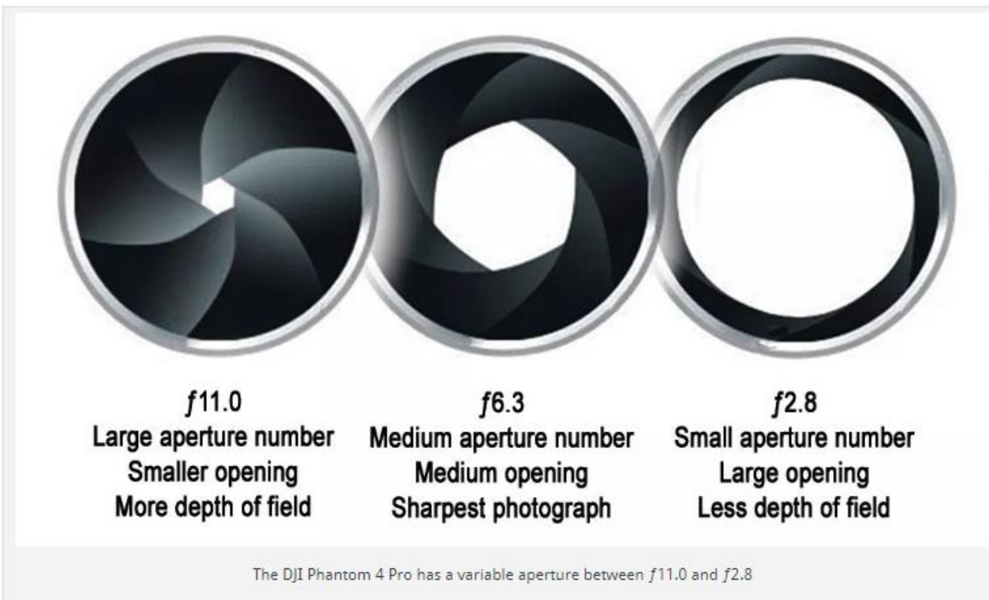


Figure 15 The value of the different aperture and the opening of lens at those aperture value

Battery: A single Phantom 4 battery, around 5870 mAh, gives a flight time of 30 minutes, more than any other drone in the same category (Jonathan Feist, 2018). Longer battery life solves the problem of frequent battery changes while flying, giving the geomechanical engineer more time to capture slope images. The long flight time also allows the drone to return to the base station safely after the battery level drops below a certain level, increasing range. The drone issues an alert when it reaches the maximum distance required for a safe journey back to the takeoff point.

It also has an advanced battery management system to prevent overcharging and over-consumption of the battery.

Price: The Phantom 4 Pro V2.0 with an additional pairs of batteries costs approximately $2,100. This is very cost-effective drone considering its professional features.

2. **Artificial Lights:** As explained previously, the main criteria for artificial light sources are light-weight, battery operated and high lumen. For this research, the Zebralight was chosen, as shown in Figure 16.

Figure 16 Zebralights used as a light source in this research (Source: Bat Conservation and Management)

The lights are high-powered LED lamps with 3 level of brightness (High- H1- 1616Lm, H2-1010Lm, Medium: M1-147Lm, M2-65Lm, Low: L1– 3.4Lm, L2-1.06Lm). The light chosen will affect the hours of usage. If longer usage is required, the output can be reduced manually. There is also an additional beacon-strobe mode. The weight of the light is about 1.4oz (39gm), which is lightweight; using two Zebralights was found not to affect the drone performance. With a battery life of more than 2 hours at high brightness under a single charge, it can be used for multiple flights.

3. Pix4D Mapper software:

Pix4D is used across the mining industry for image processing to generate point cloud data. It takes a wide range of input images, including aerial (nadir and oblique) and terrestrial images, video

(.mp4 and .avi format) and processes images based on the need for the project. It transforms images into digital spatial models and maps using cloud or desktop-based computing. The software also gives the option to assess and improve the quality of the project by selecting different processing and output options. The output options include densified point cloud, grid and raster Digital Surface Model (DSM), Digital Terrain Model (DTM), Orthomosaic 2D model, Index map, 3D textured mesh and Contour lines. The software also gives the option to select the coordinate system in which the image is captured. The step by step process of image processing has been described previously.

4. Processing desktop

For the processing of the images in PIX4D, Windows 8.1 Enterprise Operating System installed in iMac is used. It has a 64-bit processor with Intel Core i7-4771 CPU with a maximum speed of 3.50GHz. It has a total RAM of 16GB, space of 500GB and GeForce GTX 780M NVIDIA Graphics card.

5. Clamps for mounting Zebralights on the Drone

Figure 17 Clamp designed in Solidworks and manufactured in 3D printer to mount Zebralights on the Drone

Clamps for the lights, shown in Figure 17, were designed and created using a 3D printer. These were used as mounts for the Zebralights due to the ease of quickly attaching and detaching the lights in comparison to using tape. More design specification and material properties of the clamp is described in the APPENDIX B.

3.3 CHALLENGES

The use of a drone in an underground mine is a new concept and requires extensive research and development. A drone cannot be operated in an underground mine with the same flexibility as in a surface mine. An open pit mine is a vast space with no obstacles; thus, drone has the flexibility to move around and hover over equipment and monitor slopes from a safe distance without any fear of collision with the rocks, people or equipment. Most drones used in industry are equipped with collision-avoidance sensors, which are most effective while working in an open area where the obstacles are 3-4 feet away. These sensors engage and prevent the drone from getting too close to an obstacle. In the case of underground workings, however, the dimensions of drifts and walkways are much smaller, leaving a tight space for the drone to travel.

Other challenges faced by drones working in working underground include:

1. **Artificial lights**: Since there is no natural light in an underground mine, artificial lights must be used. The light should be bright enough to optimize the photogrammetry process but cannot be too bright or dull to interfere with the image capture process. Also, the light should be light-weight so that it can be mounted on the drone with ease. It is recommended from the drone manufacturers that heavy payload can affect the performance of the drone and should be avoided. However, few tests have been carried out, and battery performance is monitored during the flight suggesting that light-weight payload (~1lb). does not make much difference in performance.

2. **Stabilization correction**: For a drone to work correctly, an Inertial Measuring Unit (IMU), gyro stabilization and flight controller are essential. Drones usually rely on GPS for localization, navigation and flight control. An IMU is an electronic device that measures and reports a body's angular rate using a combination of accelerometers and gyroscopes (Wikipedia). On the surface, the gyroscope works with the IMU and satellite positioning (GPS and GLONASS) for the working and stabilization of the drone (Fintan Corigan, 2017). GPS works as a position holder for the drone, allowing it to hold one position while inspecting or capturing a picture. GPS also enables autonomous flying, allowing the pilot to avoid areas where the drone flight is restricted.

However, GPS is unavailable underground, making control and stabilization more difficult. A preferred solution to overcome GPS problem in an underground mine or closed environment is the use of a Simultaneous Localization and Mapping (SLAM) algorithm. SLAM allows the digitization of a large environment and constructs a map in real time despite incomplete information about the trajectory through the atmosphere.

3. **Autonomous drones**: Flying a drone in an underground mine with a limited light source and limited vision can be very risky and requires an experienced pilot. Flying a drone manually can make the image capture process slow and blurry as the pilot must control the drone continuously to avoid a crash. Image overlap cannot be optimized, making the point cloud of insufficient density to use for geotechnical purposes. While working in a large underground opening, it is difficult for the pilot to observe the entire working area, increasing the difficulty. Sensors installed in the drone can avoid a collision, but they are insufficient for guidance, particularly if the pilot loses line of sight. In this scenario, an autonomous drone is the best solution. Researchers at MIT are working on a solution for drones to be programmed to move quickly through a crowded and complex environment (Peter Rejcek, 2018). An autonomous drone can use the SLAM algorithm to navigate in an underground environment, avoiding crashes and optimizing the image capture process. Having an autonomous flight has the advantage that the onboard computer system will have control of the drone and it can streamline the process within time constraints and ensuring safety.

3.4 LOCATION OF RESEARCH

The San Xavier (SX) Mining Laboratory was used for performing experiments related for this research. The SX Mine is owned and operated by The University of Arizona and is the only university mining laboratory having a working vertical shaft. Students operate the mine with the assistance of an Assistant SX Director, and more than 2500 professional from mining and health, and safety industry visit the site every year. The property is located 23 miles south of Tucson and is a 90-acre facility. It has three working levels, the lowest having a depth of 150 feet. Figure 18 shows the plan view of the site. The SX mine is home to one of the most sophisticated research hoists in the country. The department renamed the mine for MGE alumnus and benefactor Hank Grundstedt in 2005 and has transformed the facility into a new resource for students, industry representatives and community members. The site has attracted a few projects from national defense, geoscience, mine safety, and mine rescue.

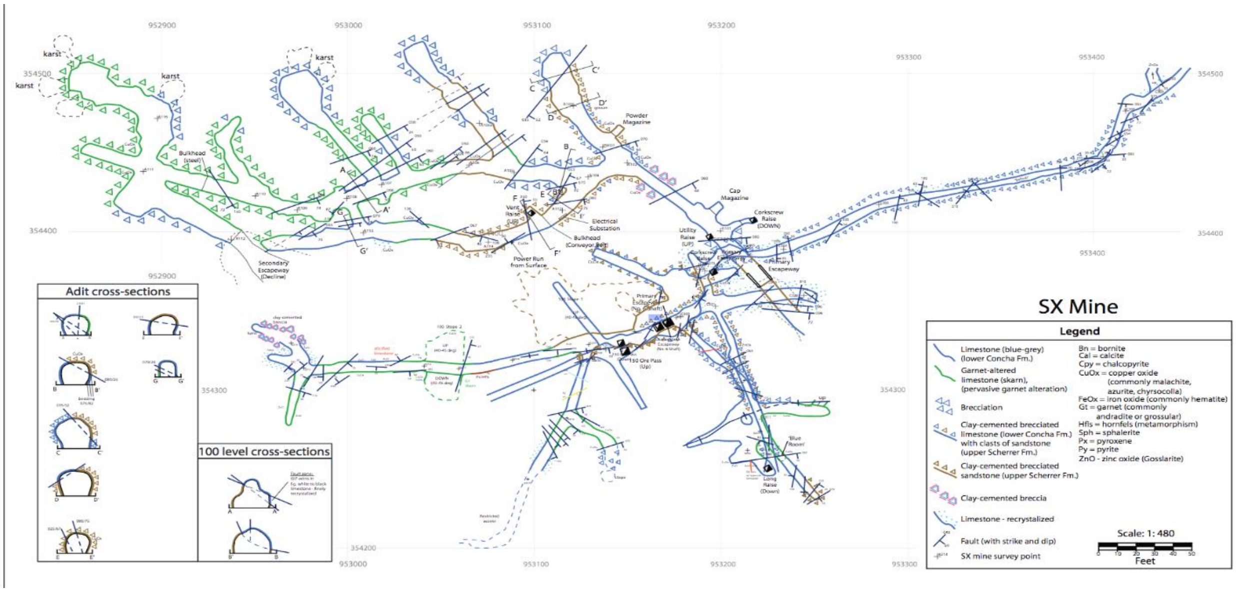


Figure 18 Plan view of the San Xavier Mining Laboratory

Fieldwork at site included learning how to fly the drone, along with performing photogrammetry on the surface in the presence of adequate light and underground in the using of artificial light. The experiment involved testing the drone in an underground environment to determine the challenges of such usage. The results of this research will also assist students to understand the geology of the rock mass, which can be used as a support to study other research projects at the site, such as like mapping of faults zone, exploring a sealed-off area, etc.

4. FLIGHT TESTING

OVERVIEW

This section of the thesis describes the different experiments performed using the drone, both on the surface and in the underground and in a variety of conditions. The tests were performed over an eight months period with the purpose of creating an effective solution to describe and support research into more effective drone usage in an underground space to generate point cloud data sets.

For the generation of the point cloud data, many different experiments were performed at the SX Mine, both underground and on the surface. Each test gives different outcomes that were utilized as a deciding factor to change the method of approach to move forward with the research. All experiments are described in the table shown below. This table shows the total number of flights performed, the location where flights was carried out, the source of light utilized, and the reason for performing the test. A further detailed description of the test flights is shown in Appendix C.

A total of 18 test flights were performed after the acquisition of the drone. The first two flights were conducted to learn how to fly the drone and its different functionality, with the remaining flights carried out as test experiments to capture images for photogrammetry. More detailed information of the test flights is described later in this thesis.

Table 1: Details of all 18 test flights performed.

FLIGHT NUMBER	LOCATION OF TEST FLIGHT	LIGHT SOURCE	REASON FOR PERFORMING TEST
1	SX MINE, SURFACE	NATURAL LIGHT	TO LEARN ABOUT THE FUNCTIONING OF THE DRONE
2	SX MINE, SURFACE	NATURAL LIGHT	TO LEARN MORE ABOUT CONTROLLING THE MOVEMENT OF THE DRONE WHILE FLYING
3	SX MINE, SURFACE	NATURAL LIGHT	TO CAPTURE THE IMAGES OF ROCK IN FRONT OF THE ADIT TO PERFOM PHOTOGRAMMETRY
4	SX MINE, DECLINE	NATURAL LIGHT	TO STUDY THE BEHAVIOR OF DRONE MOVEMENT IN AN UNDERGROUND SPACE
5	SX MINE, IN FRONT OF THE ADIT	NATURAL LIGHT	TO STUDY THE DENSITY AND SPACING OF THE POINT CLOUD GENERATED BY THE DRONE
6	SX MINE, DECLINE	ARTIFICIAL LIGHT, 4 PIECE OF 500W, 102 VOLT HALOGEN LIGHT	TO OBSERVE AND ANALYZE THE EFFECT OF USING ARTIFICIAL LIGHT IN GENERATION OF POINT CLOUD
7	PEPPER SAUCE CAVE	ZEBRA LIGHTS USED BUT NOT MOUNTED ON THE DRONE	TO TEST THE DRONE IN BIGGER SPACE
8	SX MINE, DECLINE	MICRO LED LIGHTS USED	TO ANALYZE THE POINT CLOUD GENERATED BY USING MICRO LED LIGHTS MOUNTED ON DRONE
9	SX MINE, IN FRONT OF THE ADIT	ZEBRALIGHTS	FIRST FLIGHT AFTER MOUNTING ZEBRALIGHTS TO PRODUCE POINT CLOUD
10	SX MINE, 100 FEET LEVEL	ZEBRALIGHTS	TO OBSERVE THE BEHAVIOR OF DRONE AT 100FT LEVEL
11	SX MINE, 100 FEET LEVEL	ZEBRALIGHTS	TO CAPTURE IMAGE FPR POINT CLOUD GENERATION AND COMPARING IT WITH THE LIDAR POINT CLOUD
12	SX MINE,SURFACE	NATURAL LIGHT	TO FIND THE NOISE IN THE POINT CLOUD GENERATED BY SCANNING A PLANE SURFACE
13	ROCK MECHANICS LAB, MINES BUILDING	ZEBRA LIGHTS (AUTO MODE)	BECAUSE OF ARMY TRAINING AT SX MINE, FLIGHT TEST WERE PERFORMED AT ROCK LAB AT MINES BUILDING
15	SX MINE, IN FRONT OF THE ADIT	ZEBRALIGHTS(AUTO MODE)	TO GENERATE THE POINT CLOUD USING ZEBRALIGHTS CONSIDERING SURFACE TO BE AN IDEAL UNDERGROUND CONDITION
16	SX MINE, IN FRONT OF THE ADIT	ZEBRA LIGHTS(MANUAL MODE)	TO GENERATE THE POINT CLOUD USING ZEBRALIGHTS CONSIDERING SURFACE TO BE AN IDEAL UNDERGROUND CONDITION
17	SX MINE, SURFACE	NATURAL LIGHT(AUTO MODE)	TO FIND THE NOISE IN THE POINT CLOUD GENERATED BY DRONE error check to find noise in the point cloud
18	SX MINE, SURFACE	ZEBRALIGHTS	TO PERFORM THE CHANGE DETECTION IN POINT CLOUD

TEST FLIGHT 1 AND 2

The first step after acquiring the drone was to test it on the surface. Test flights 1 and 2 were performed on the surface to learn about the different functionality of the drone and how the collision avoidance sensors work. While performing tests 1 and 2, no point cloud was generated.

Table 2: Test flight 1 and 2 details

Flight number	Location of test flight	Date performed	Number of images captured	Number of points generated	Point density	Image scale
1	SX Mine, surface	9/14/2018	N/A	N/A	N/A	N/A
2	SX Mine, surface	9/15/2018	N/A	N/A	N/A	N/A

TEST FLIGHT 3, 4 AND 5

Test flights 3 and 5 were performed on the surface and 4 was performed in the decline to capture images for processing in the PIX4D software. These images were cloud processed and not desktop processed, and the point density was set at optimal and image scale is set at half the image size scale in PIX4D. The results of changing the output variables, such as point density, image scale, and number of matching points is further discussed in the Results and Analysis sections. Figure 1 shows the image captured by test flight 4 in the decline. Note that the quality of the image is poor as there was not enough light to perform the photogrammetry optionally.

It was determined during the test flight 4 that there is a requirement of an artificial light source to illuminate the rock masses so that sharp images can be acquired, which helps in the photogrammetry process. In the presence of blurred and distorted images, the photogrammetry process generates noise in the point cloud, which delays the processing time and is unfavorable from the geomechanical point of view. The learning outcome after performing test flight 4 is to perform the same test in the decline in the presence of artificial light sources.

Table 3: Test flight 3, 4, and 5 details

Flight number	Location of test flight	Date performed	Number of images captured	Number of points generated	Point to point spacing	Point density	Image scale
3	SX Mine, surface	9/21/2018	64	3,551,528		Optimal	Half image size
4	SX Mine, decline	9/21/2018	21	2,021,731	0.361524	Optimal	Half image size
5	SX Mine, in front of the adit	9/21/2018	64	3,564,340		Optimal	Half image size

Figure 19 The image of decline while performing test 4

TEST FLIGHT 6

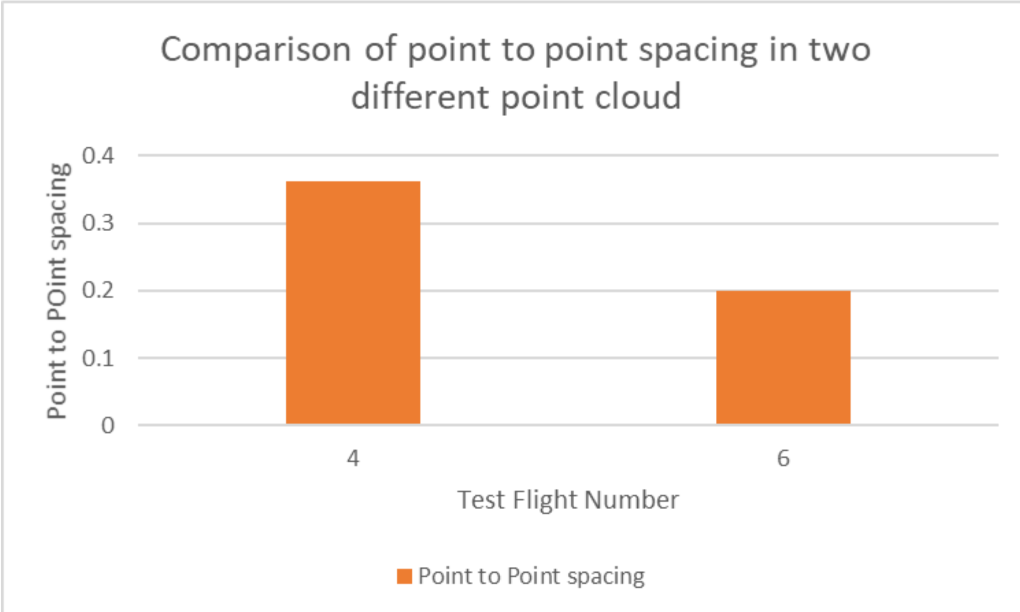
Test flight 6 was performed in decline at the SX Mine with the help of an artificial light source. Halogen lights mounted on the tripods were 500W, 102 volts and have an output of 8000 Lumens. The details of the flight are shown in the below table. The normalized point spacing of the point cloud set after processing the image is calculated to be 0.199456. This value of point spacing is a relative value for comparison and not in feet or meter. This point spacing value from test flight 6 is compared with the value from test flight 4, shown in figure 2. The lower value of the test flight 6 shows that the results from test flight 6 is denser than the test flight 4.

Table 4: Test flight 6 details

Flight number	Location of test flight	Date performed	Number of images captured	Number of points generated	Point to point spacing	Point density	Image scale
6	SX Mine, Decline	9/28/2019	26	1,274,542	0.199456	Optimal	Half image size

Figure 20 The setup of halogen lights for flight test 6

After test flight 6, the images were processed in the software and it was observed that there were voids in the point cloud data, as can be seen in figure 21. An analysis of images captured by the drone from different position and angles makes was made, and it indicated that a fixed light source results in some dark images that form voids in the point cloud after processing the images. The solution to this problem was to mount the light sources on the drone itself. The light will follow the path of the drone, creating uniform lightning of the images and an improved point cloud. Attaching the light source to the drone itself is also a much more practical solution.



Graph 1: The spacing between two points in point cloud generated by test flight 4 and 6. (The value on Y axis is normalized value and not in feet or centimeter)

Figure 21 Voids in the point cloud after test flight 6

TEST FLIGHT 7 AND 8

Flight 8 was performed in the decline using micro LED lights. These were selected due to their light weight and ease of attachment to the drone, and their integrated batteries. After performing flight 8, the images were captured and processed in the PIX4D software. The software was not able to process the picture as the light source was not bright enough to capture sharp images, making it hard to generate the point cloud. The quality of the image from test flight 8 can be seen in figure 4. The same problem arises while processing the image acquired by the flight 7 in the Pepper Sauce cave. The case was big enough but, due to lack of proper lighting, the image capture was blurred, and point cloud data could not be generated. The details of the test flight 7 and 8 is shown in table below.

Table 5: Test flight 7 and 8 details

Flight number	Location of test flight	Date performed	Number of images captured	Number of points generated	Point density	Image scale
7	Pepper sauce cave	10/14/2018	50	n/a	Optimal	Half image size
8	SX Mine, decline	11/2/2018	3	n/a	Optimal	Half image size

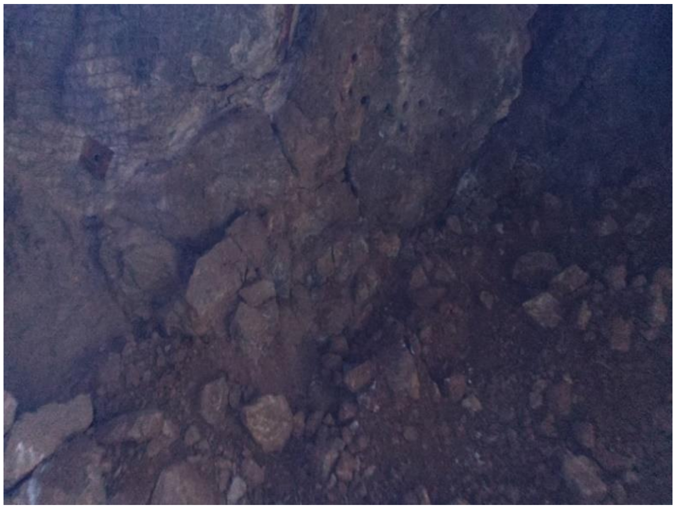


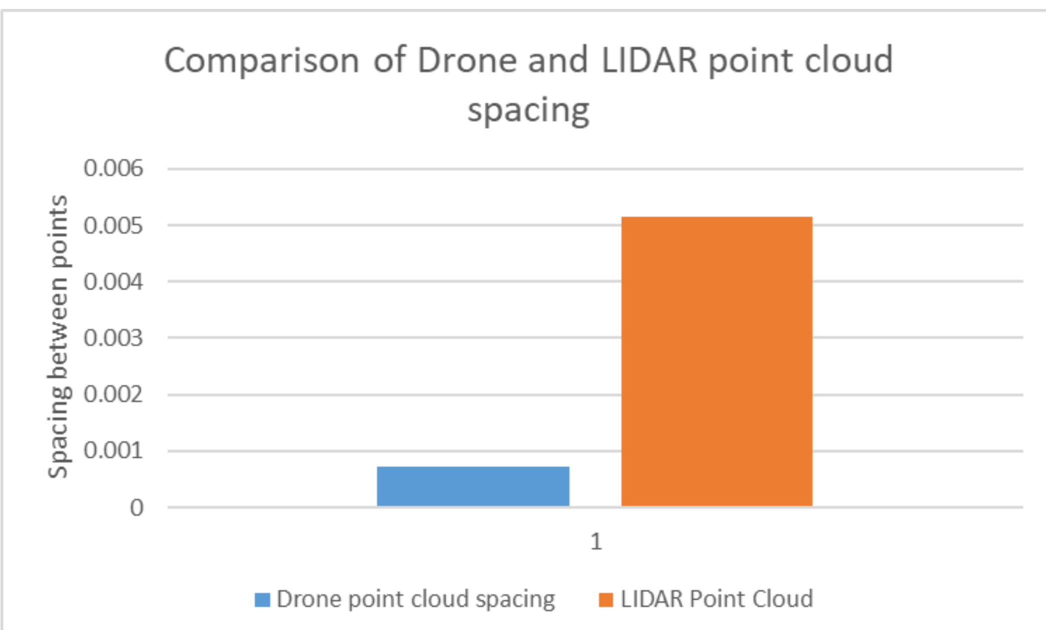
Figure 22 The quality of image after performing test flight 8

TEST FLIGHT 9, 10, AND 11

After performing flight 8, Zebralights were used for performing all remaining experiments. The specification and reason for selection of Zebralights are described in section 3.2. After mounting Zebralights on the drone, flights 9, 10 and 11 were performed on the surface and at the 100feet level at the SX Mine. The results from the test are shown in the table below. The point spacing from the test results were plotted in a graph and is shown below. The results suggest that point spacing is lower compared to point spacing in a LIDAR-generated point cloud. The learning outcome from this test shows that the Zebralights are a good source of artificial light and can be used in underground drone photogrammetry.

Table 6: Test flight 9, 10 and 11 details

Flight number	Location of test flight	Date performed	Number of images captured	Number of points generated	Point density	Image scale	Point spacing
9	SX Mine, in front of the Adit	11/16/2018	34	1,903,922	Optimal	Half image size	0.005156
10	SX Mine, 100 feet level	1/31/2019	N/A	N/A	Optimal	Half image size	
11	SX Mine, 100 feet level	2/5/2019	164	43,311,476	High density	Original image size	0.000720



Graph 2: The graph shows the distance between point cloud generated by the drone during flight 11 and LIDAR point cloud (The value on Y-axis is normalized value and not in feet or centimeter)

TEST FLIGHT 12 AND 17

While performing tests at the 100 feet level at the SX Mine where there is no GPS signal, the drone was continually drifting around, making it hard to pilot. This could have caused damage to the drone due to collision. So, from the safety point of view, the rest of the flights from 11 through 18 were performed on the surface and during night time to test in a dark environment. Test flights 12 and 17 were performed on the surface to observe the noise in the point cloud generated by the drone photogrammetry. After processing the images from the scan and analyzing the point cloud data, it was observed that uniform regions of light colors, white for instance, causes noise in the point cloud noise as compared to heterogeneous regions of mixed colors and textures, as shown in figures 6 and 7. The reason for the noise is thought to be due to the software being unable to pick out specific points for the pattern matching part of photogrammetry. This is a possible research topic for future work.

Table 7: Test flight 12 and 17 details

Flight number	Location of test flight	Date performed	Number of images captured	Number of points generated	Point density	Image scale
12	SX Mine, surface	3/16/2019	71	4,295,519	Optimal	Half image size
17	SX Mine, surface	4/6/2019	33	22,849,123	High density	Original image size

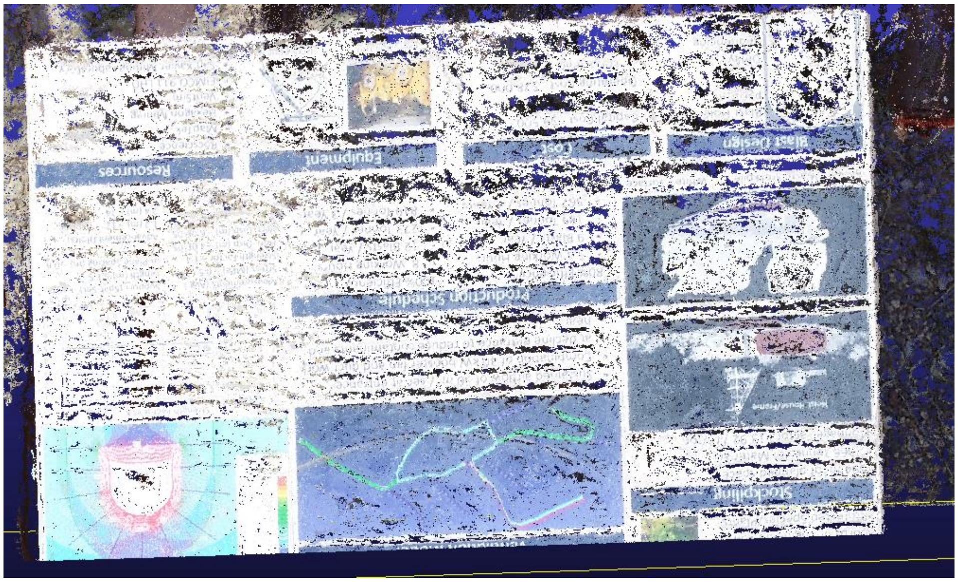


Figure 23 Noise generated after scanning a piece of flat surface. The white portion has significant amount of noise as compared to other section with texts

TEST FLIGHT 13, 14

Test flight 13 and 14 are identical flights and were performed in the rock mechanics lab of the Mines Building at the University of Arizona. These flights were performed to understand the difference in point cloud details generated when changing the camera settings. Test flight 13 was carried out in the Auto mode of camera, while test flight 14 was carried out in the Manual mode. Image specifications are shown in the table below. The results after generating the point cloud show that flight 14 has more spots with dark patches. This must have happened because at fixed ISO value, camera absorbs a certain amount of light irrespective of the distance from the object. This produces darker patches than have a well illuminated image. However, in case of flight 13, the auto ISO mode made camera change the light absorbance depending on the distance from the object.

The learning outcome from test flights 13 and 14 suggest that the image capture must be done in Auto mode. The Phantom 4 camera is smart enough to change the setting to create a sharp image. PIX4D also suggest capturing images in auto mode when light source is limited.

Table 8: Test flight 13 and 14 details

Flight number	Location of test flight	Date performed	Number of images captured	Number of points generated	Point density	Image scale
13	Rock mechanics lab, Mines building	3/31/2019	47	24,918,603	High density	Original image size
14	Rock mechanics lab, Mines building	3/31/2019	36	19,205,618	High density	Original image size

Table 9: Details of camera setting while performing test flight 13 and 14

Flight number	F-stop	Exposure time (sec)	ISO speed	Focal Length (mm)	Aperture
13	f/3.2	1/30	100	9	2.97
14	f/7.1	1/120	1600	9	2.97

TEST FLIGHT 15, 16, AND 18

The point clouds generated from the test flights 15, 16 and 18 are the basis for some of the key results from this thesis. While performing previous flights in decline, 100 feet level and rock lab, it was observed that there is a high chance for the drone to crash, as space was limited, and the lack of GPS destabilized the drone. Hence, an assumption was made that tests performed on the surface during night could serve as an adequate facsimile for an underground environment. Test flights 15, 16 and 18 were performed during night hours at the SX Mine.

Flight test 18 was performed for demonstrating the effectiveness of the change detection in dark environments. Artificial change was created, and “before” and “after” videos were captured, and from this, point cloud subtraction was conducted and the change was analyzed. The low number of points for test flight 18 is due to it being processed in cloud mode and not in desktop mode.

Table 10: Test flight 15, 16 and 18 details

Flight number	Location of test flight	Date performed	Number of images captured	Number of points generated	Point density	Image scale
15	SX Mine, in front of the Adit	4/3/2019	21	7,331,958	High density	Original image size
16	SX Mine, in front of the Adit	4/3/2019	31	17,708,716	High density	Original image size
18	SX Mine, Surface	4/22/2019	134	7,555,374	Optimal	Half image size

5. RESULT AND ANALYSIS

The results and analysis presented in this chapter focus on test flights 5, 11, and 18. Details on these flights are shown in table 11 below. Table 12 shows details on the LIDAR point clouds which were used as comparison with the results of drone flights 5, 11, and 18.

Table 11: Details of test flight 5, 11, 17 and 18

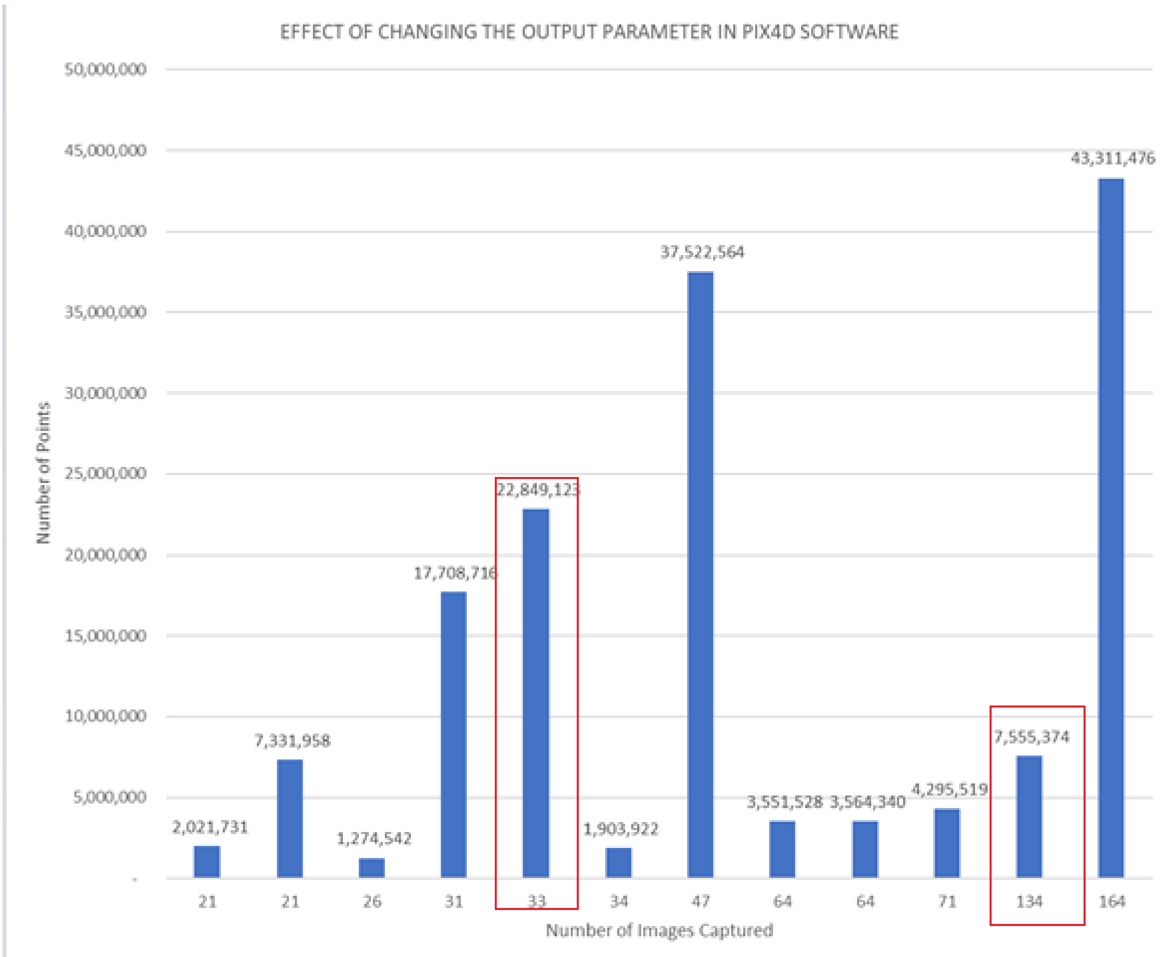
Flight number	Location of test flight	Date performed	Number of images captured	Number of points generated	Point density	Image scale
5	SX Mine, in front of the Adit	9/21/2018	64	4	Optimal	Half image size
11	SX Mine, 100 feet level	2/5/2019	164	43	High density	Original image size
18	SX Mine, Surface	4/22/2019	134	8	Optimal	Half image size

Table 12: Details of LIDAR point cloud (FARO Scanner)

LIDAR Scan Number	Scanning location	Date Scanned	Number of points
1	100 feet Level, SX Mine	1/31/2019	41,004,382
2	SX Mine, Surface, In front of the Adit	4/27/2019	1,676,857

ANALYSIS 1

After processing the images from all the test flights, point clouds were generated, and a comparison was made between the number of images processed and the number of points generated. The result is shown in graph 3. This analysis suggests that a dense point cloud can be generated by using the same number of images, and changing the output parameter in the PIX4D software. For example, test flight 17 with only 33 images, produced a cloud with more points than test flight 18 with 134 images. Changing the value of point density and the image scale size changes the test results greatly. This suggests that even with a smaller number of images, a dense point cloud can be generated.



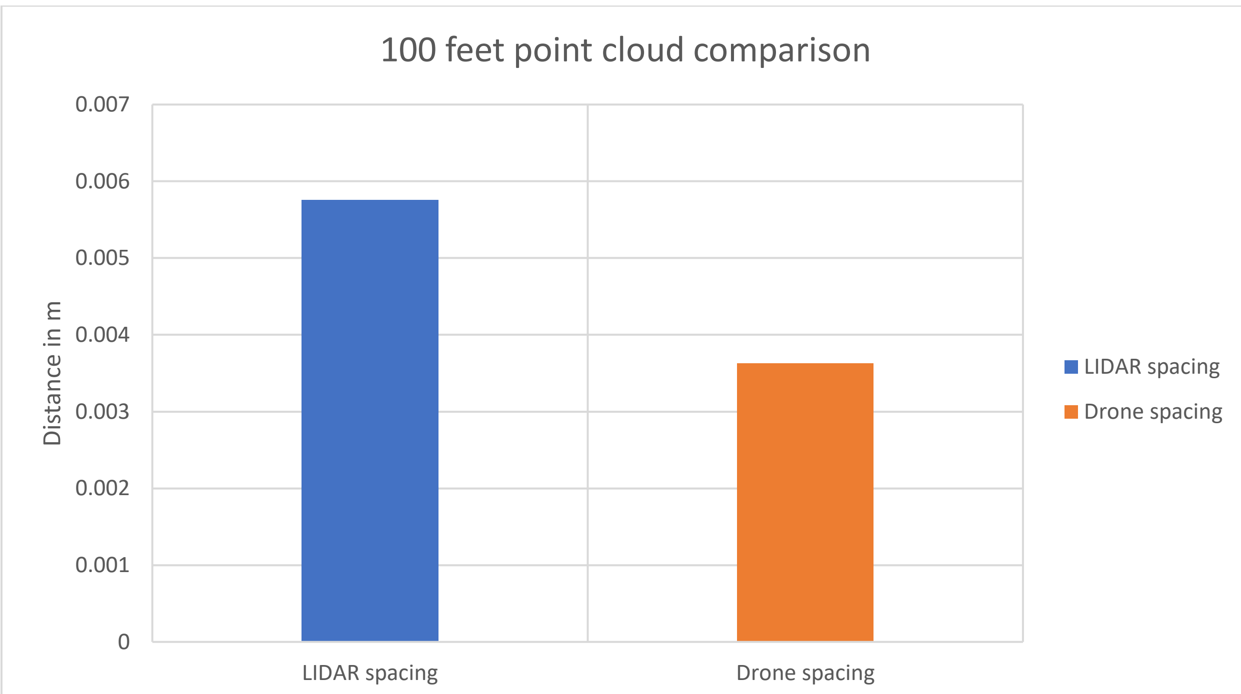
Graph 3: This graph demonstrates the effect of changing the output parameter in the PIX4D software like point density and image scale can change the total number of points generated.

ANALYSIS 2

The point density is compared between the point cloud of test flight 11 and 18 and the LIDAR point cloud from scan number 1 and 2. The point to point distance is calculated after registration of the point cloud from test flight 17 and the LIDAR point cloud. Registration is required to bring both point cloud sets to the same scale, so that a relative comparison can be carried out. In this case, the drone point cloud is registered against the LIDAR point cloud, which brings the drone point cloud to the scale of LIDAR point cloud. By default, the LIDAR point cloud was captured in the unit of a meter with point spacing being 1/4th. 1/4th value of spacing means LIDAR is going to capture every 4th point and this is a variable parameter which can be modified according to the need of the project. The comparison made can be seen in graph 4 and 5.

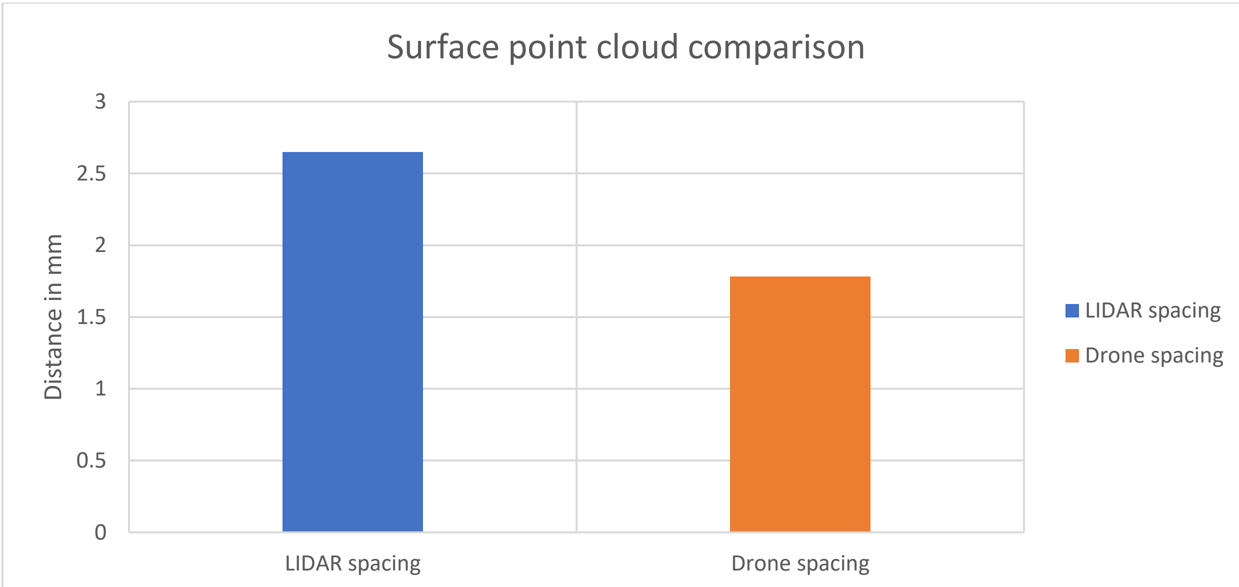
Table 13: The result of the two points distance on the surface and at 100 feet level for Drone point cloud and LIDAR point cloud.

	Scan Number	Test flight No.	LIDAR spacing	Drone spacing
Point to Point Spacing in m at 100 feet Level	1	11	0.005761	0.003628
Point to Point Spacing in mm on surface	2	18	2.6484	1.7807



Graph 4: Comparison of point spacing between point cloud from LIDAR scan 1 and test flight 11

The value on Y-axis on graph 4 and 5 is in m. The less value of drone spacing in both graph 4 and shows that the point cloud produced by drone at 100 feet level and on the surface is of comparable density than the point cloud produced by the LIDAR at the same place. This comparison is just one scenario of looking at the quality of point cloud. However, analysis of the resolution of the point cloud data will give a better understanding of the quality of point cloud.



Graph 5: Comparison of point spacing between point cloud from LIDAR scan 2 and test flight 17

In general, there are two important parameters in a point cloud, point density and point resolution. Point resolution refers to the accuracy of the X, Y, Z locations determined by drone or LIDAR, compared with the actual locations. There are different ways to test the resolution, and these methods were utilized in this research. One method is to closely examine a scanned flat surface to observe the artificial "roughness" that occurs due to point resolution. The change between two-point clouds of the same scene at different times or with different scanners is another method to assess point resolution. For the scan distances discussed in this thesis (5-25 meters), an excellent point cloud error would be a one or two millimeters or less; a noisy point cloud might have error on the order of centimeters.

All point clouds contain noise irrespective of the scanning method used. While comparing point cloud data from test flight 11 and LIDAR scan 1 and after cutting a flat surface to examine the noise "thickness", it was observed that the noise in the LIDAR point cloud is much smaller than the noise in the drone point cloud. Figure 24 shows that the difference could be a factor of three or more. The red area is the LIDAR point cloud and the yellow area is the drone point cloud.

There are several possible reasons for the reduced resolution of the drone point clouds. Dust is one possibility, due to dust that becomes airborne due to the strong air currents produced from the drone. Treating the walls and floor of the underground excavations with water mist could reduce this dust. A second source of error in the drone point clouds originates from the quality of the images used in the photogrammetry. A quality image is sharp and the lighting is uniform. A cloudy day on the surface, for example, produces excellent images for photogrammetry. Image sharpness depends on settings in the drone camera, most importantly the shutter speed. The parameters of the lights mounted on the drone will influence the uniformity of the lighting. Parameters of the lights include the lumens, the spread angle of the light, and the color content of the light. These parameters could be optimized in the future to increase image quality and thereby increase the resolution of the point cloud.

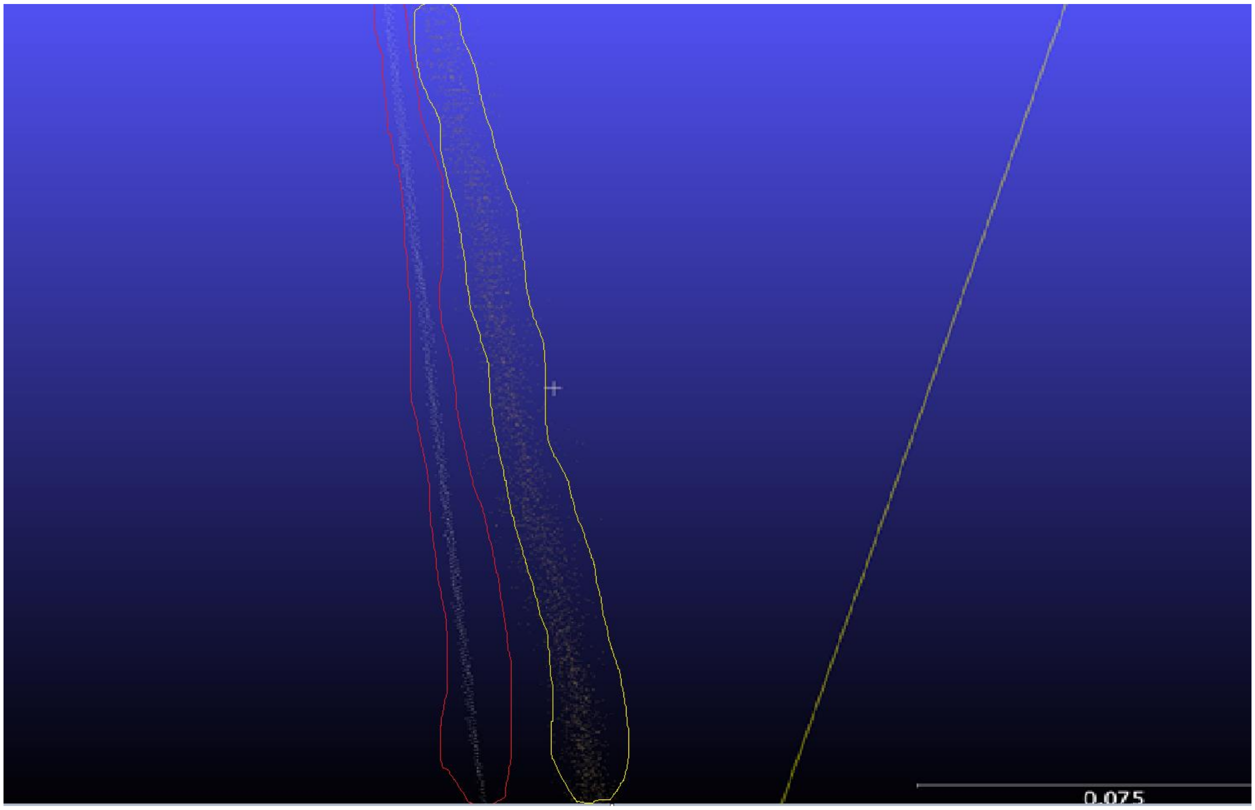


Figure 24 A comparison of the point cloud data of a flat surface for thickness. The red area is a point cloud from LIDAR and yellow is point cloud from the drone

ANALYSIS 3

The third analysis includes the point cloud from test flight 11 and LIDAR-generated point cloud scan number 1. In this analysis, change detection was performed between both point clouds at the 100 feet level in the SX mine.

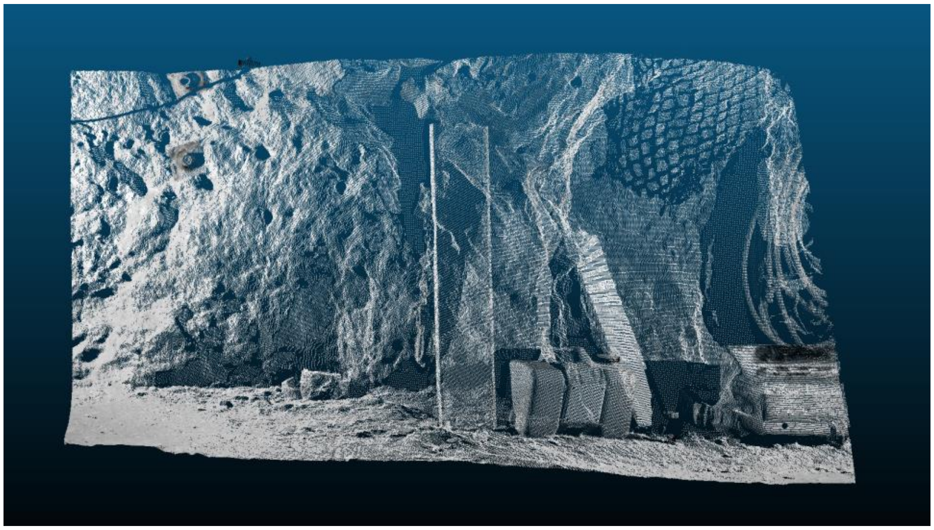


Figure 25 The LIDAR point cloud from the FARO scanner

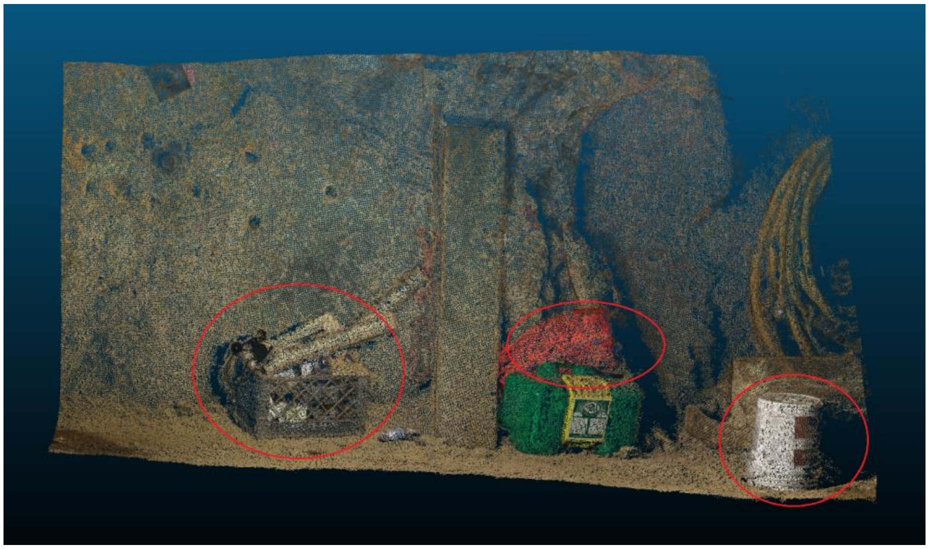


Figure 26 Drone point cloud from test flight 11 at 100 feet level at the SX Mine. The red circle shows the object that is not present in the LIDAR point cloud

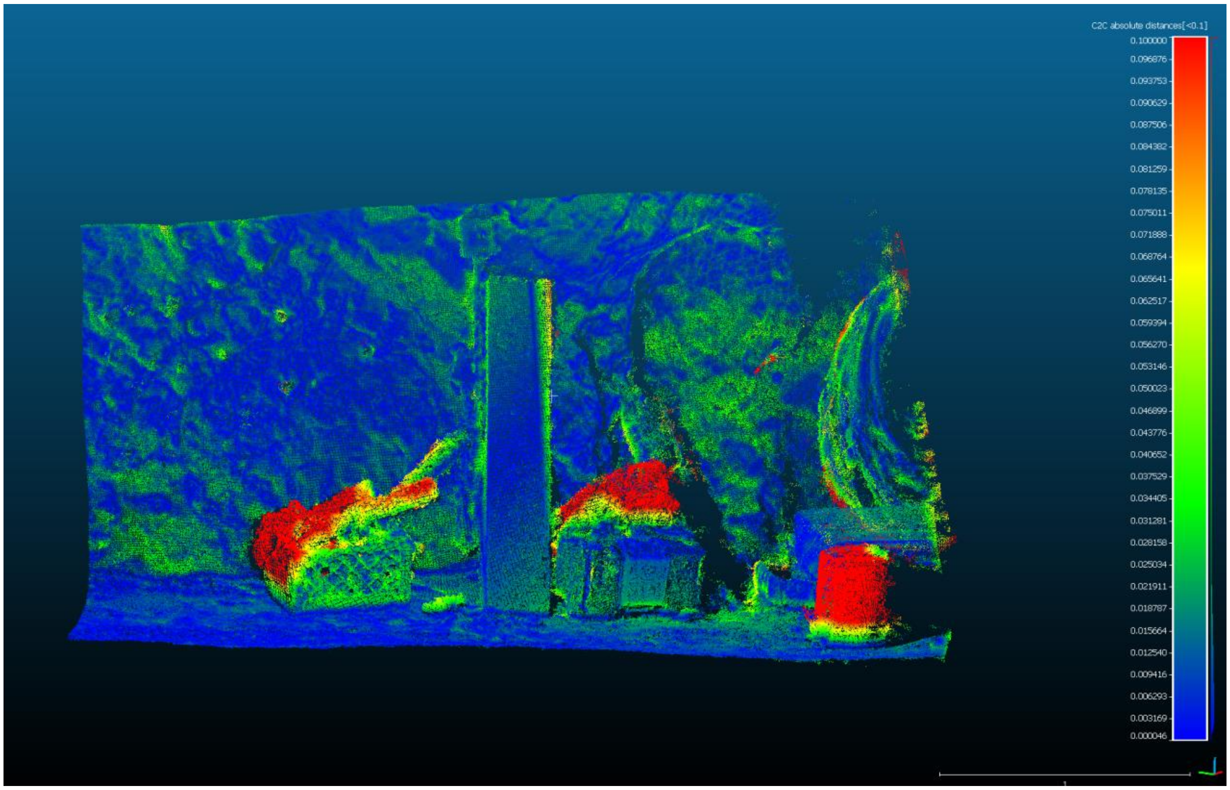


Figure 27 The result after performing change detection between test flight 11 and LIDAR scan 1

The differences between both point clouds can be observed in figure 26. Objects circled in red are not present in the LIDAR point cloud but are present in the drone cloud. Figure 28 shows the histogram distribution of the scalar field color after performing change detection. This histogram shows that, on the right side of the histogram, the red color has a significant value indicating the change between the two clouds.

For comparing the accuracy of detection made by the Cloud Compare software and actual movement of the points, 5 different measurements were made manually. Those values were compared to the 5 different measurements detected by the software, with the results shown in graph 6. The results show that the measurements made manually are close to the change detected automatically. However, the smallest change detection that can be made is in the range of centimeters, not millimeters. This agrees with the results shown in Figure 24. This range of change detection suggests that the point cloud can detect rock movement and opening of significant fractures in slopes in the range of centimeters. This result indicates that the point cloud data produced by drone is capable of being used in the detection of fairly major rock movement which could come from rockfall events and significant room closure. The value of all the 10 measurements used for changed detection is shown in Appendix D.

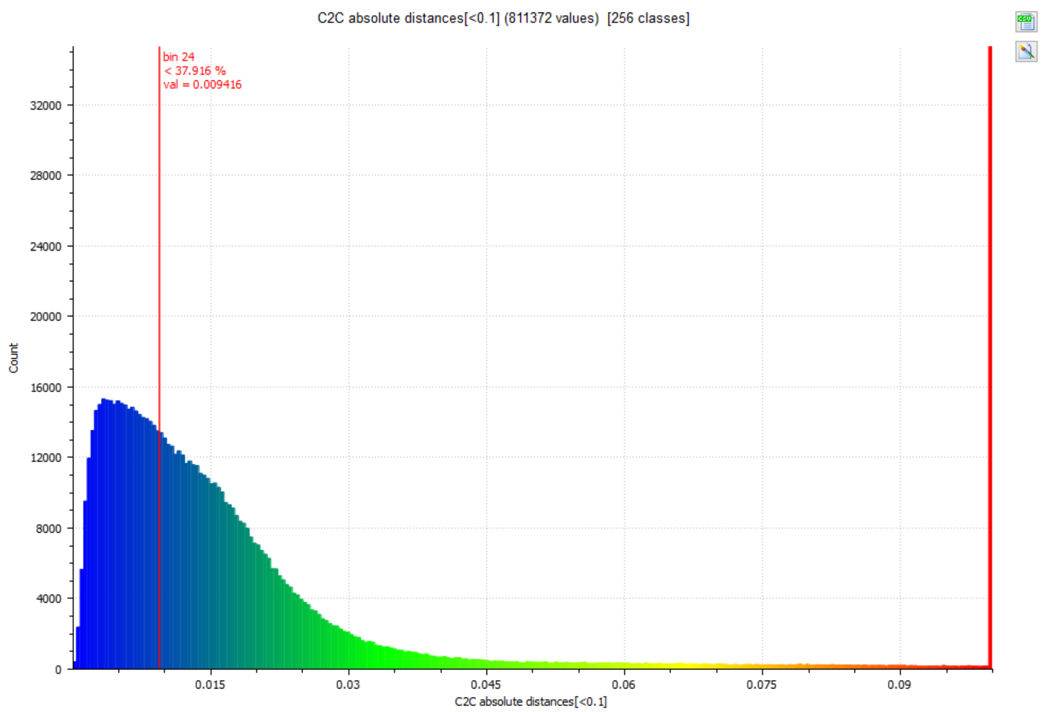
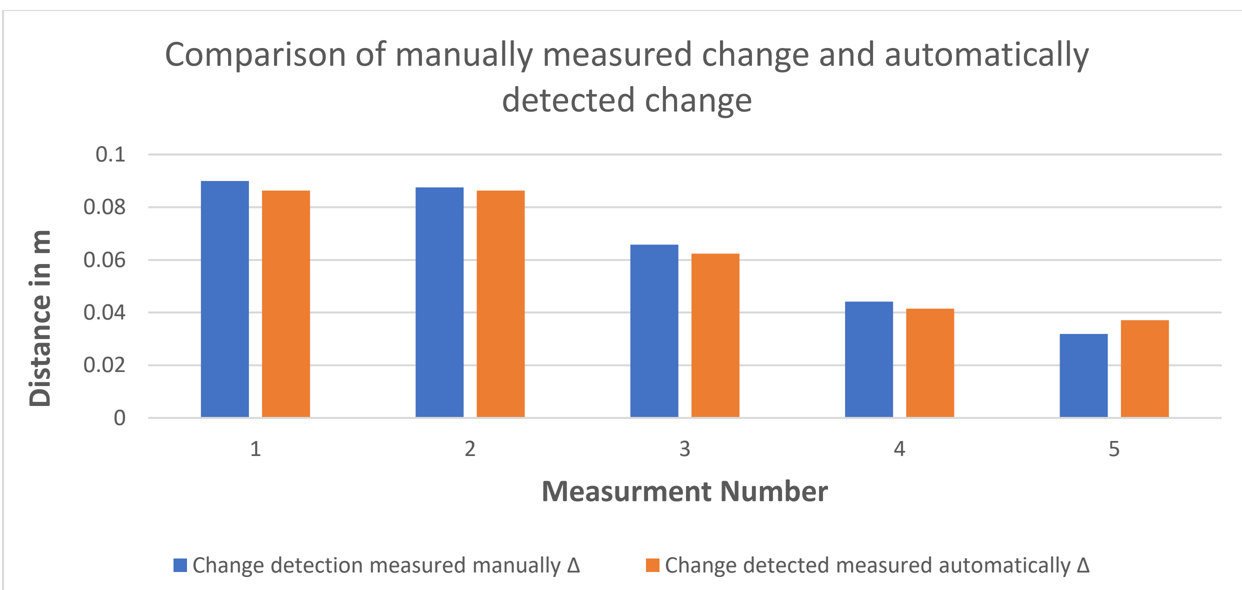


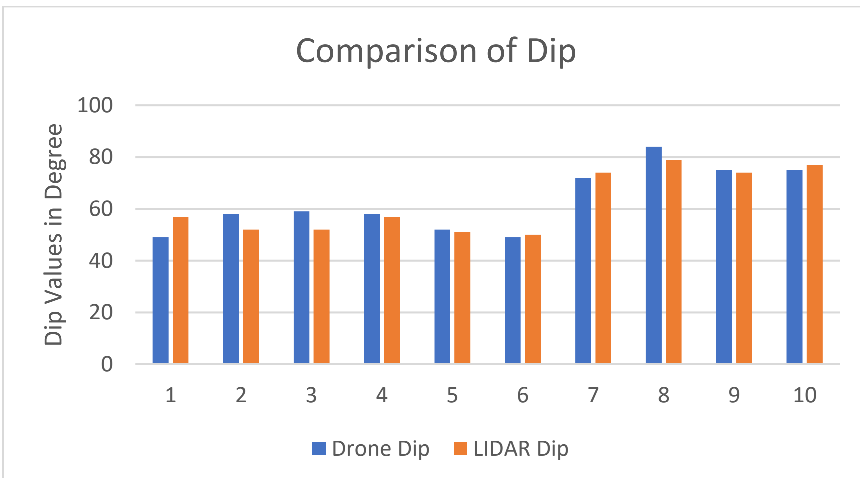
Figure 28 Histogram showing the distribution of point cloud scalar color after performing change detection.



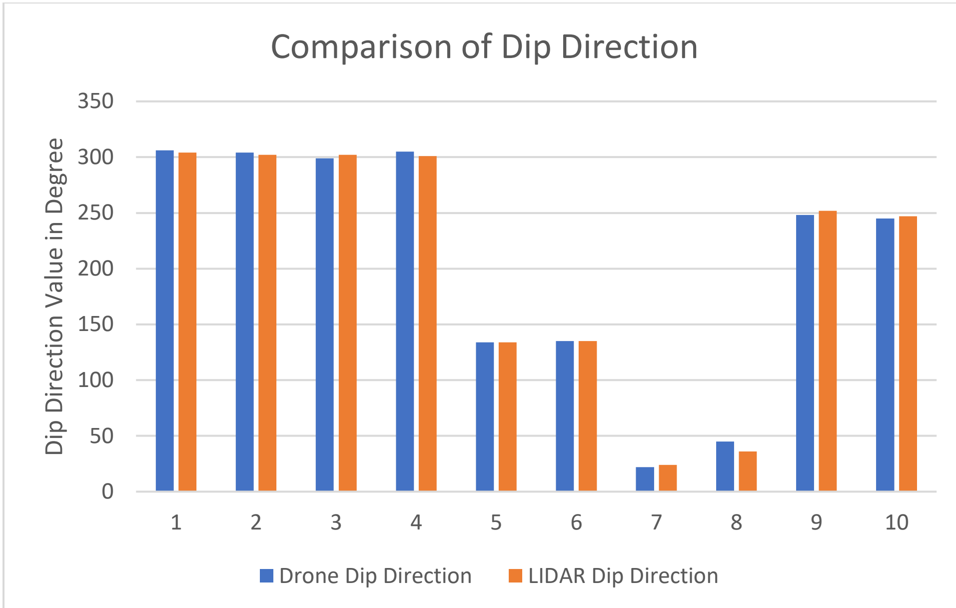
Graph 6: Comparison of the change detection measured manually and automatically using the cloud to cloud distance

ANALYSIS 4

The point cloud generated by test flight 18 and LIDAR scan 2 is used to analyze the accuracy of extracting fracture information, particularly fracture orientation, from the drone point cloud. A spot was selected in both point cloud data sets from where rockfall happens and in 10 different surface planes. The dip and dip direction values of those planes were plotted in Dips software to generate a stereonet showing the shift in the location of pole vectors compared to each other. Figure 29 shows the stereonet and the change in the values of dip and dip direction for the drone (shown by◆) and LIDAR (shown by X).



Graph 7: Comparison of Dip value for plane generated in Drone and LIDAR point cloud



Graph 8: Comparison of Dip Direction value for plane generated in Drone and LIDAR point cloud

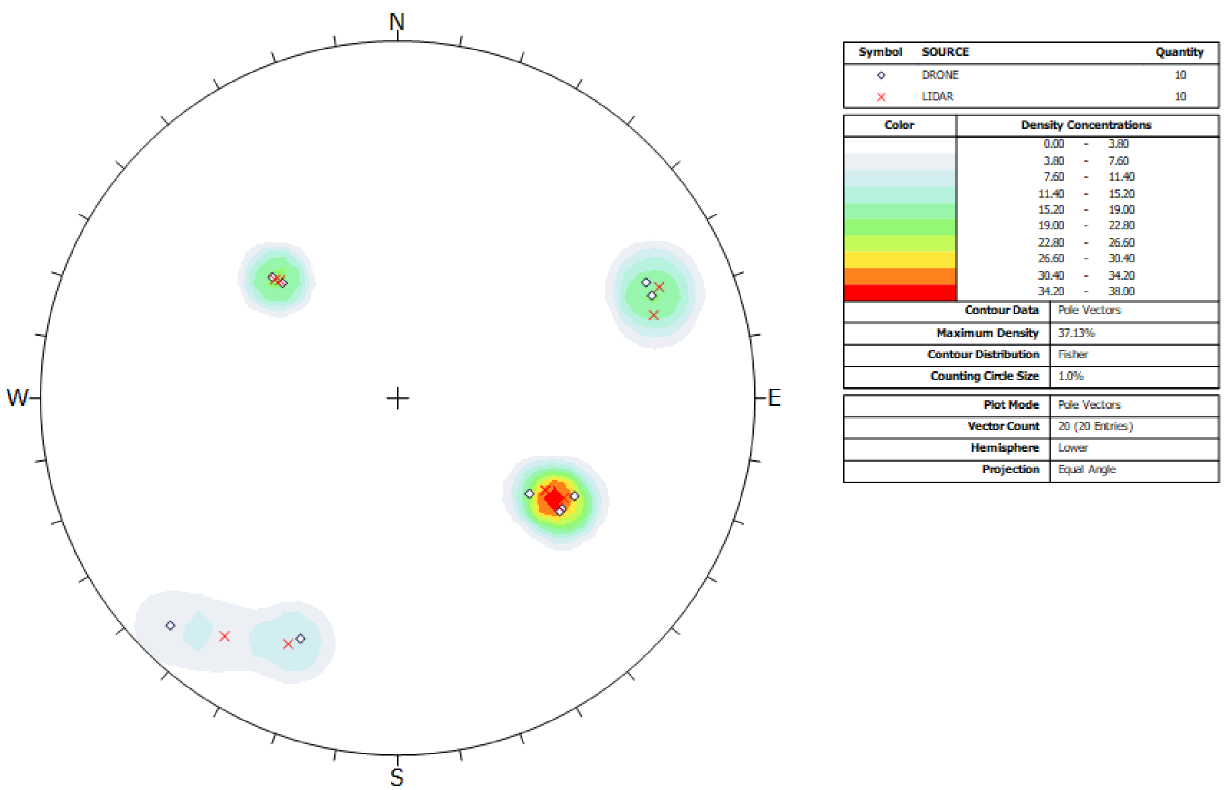


Figure 29 Stereonet projection of 20 different planes generated by Drone and LIDAR point cloud

After analyzing the results generated utilizing the Rocscience Dips software, it can be concluded that for all fracture surfaces except very small ones (smaller than 0.05 m^2 area), the drone point cloud determines fracture orientation with equal accuracy compared with a high-resolution LIDAR scanner. It is expected that fracture spacing can also be extracted from drone point clouds with equal accuracy to LIDAR, but at this time it is not recommended for calculating joint roughness, which often involves peaks and troughs with heights on the order of millimeters.

6. CONCLUSIONS

This thesis described an innovative approach to utilizing drones in an underground environment for geotechnical monitoring. This involved the use of the DJI Phantom 4 drone with a pair of mounted Zebralights for image capture and the generation of three-dimensional point cloud data. The use of Zebralights solves the illumination problem underground, allowing the collection of quality pictures for the photogrammetric process and was found to yield sufficiently high-resolution point clouds for extracting geotechnical information such as fracture orientation, fracture spacing, and rock mass movement.

Since underground terrestrial LIDAR has previously been shown by many researchers to produce point clouds of enough quality for geotechnical purposes, in this research drone point clouds were compared with LIDAR point clouds taken from the same underground locations.

The following conclusions can be drawn from the research described in this thesis:

- Following the guidelines as outlined in this thesis, drones can be used in an underground mine for geotechnical monitoring.
- The point clouds produced by a drone in an underground environment can have a point cloud spacing at least as dense (on the order of millimeters) and very comparable to point clouds generated by a LIDAR scanner.
- The resolution of the individual points in a point cloud generated by an underground drone contains additional noise compared to the noise generated from LIDAR underground. This was found to be due to several factors, including dust generated by the drone, non-uniformity of the light conditions resulting in darkness in some captured images, and the quality of the light color from the Zebralights which were used.
- Despite the lower point resolution, it was found that the drone point clouds could still be used for extracting important geotechnical information which includes fracture orientation and change detection. For change detection, rock mass movement greater than 1cm was able to be detected using the underground drone point clouds collected in this research.
- Underground point cloud generation from drones was found to be efficient and fast. The drone equipment and point cloud generation software is also very inexpensive compared with the cost of LIDAR systems.

The conclusions given above are the result of 8 months of research. During this research, 18 test flights in different environments and conditions were conducted, mostly at the University of Arizona San Xavier (SX) Experimental Mine. All test flights were methodically planned and executed, to produce high-quality results that can either form the basis for additional research in the future, or be implemented in actual mining environments.

Drone use in the mining industry is the future of monitoring and surveying. Effective use of drones in an underground mine will increase safety, reduce costs, and save time.

7. RECOMMENDATIONS

Several recommendations for future work are given below.

1. One of the challenges of using a drone in an underground mine is stabilizing drone movement without the use of GPS. A possible future solution is to mount an additional Inertial Measuring Unit on the drone. This could provide stability to the drone while flying in the absence of GPS.

2. Another problem observed while performing this research was the resolution of the point cloud. In the presence of dust and artificial lights mounted on the drone, the point cloud contains noise that reduces its ability to be used for precise change detection. There are many future methods that could be implemented to reduce underground dust prior to drone scanning, including water and proper ventilation. With regards to the artificial lights, other light sources mounted to the drone can be investigated in the future. Implementing these recommendations should increase the resolution of the point cloud data.

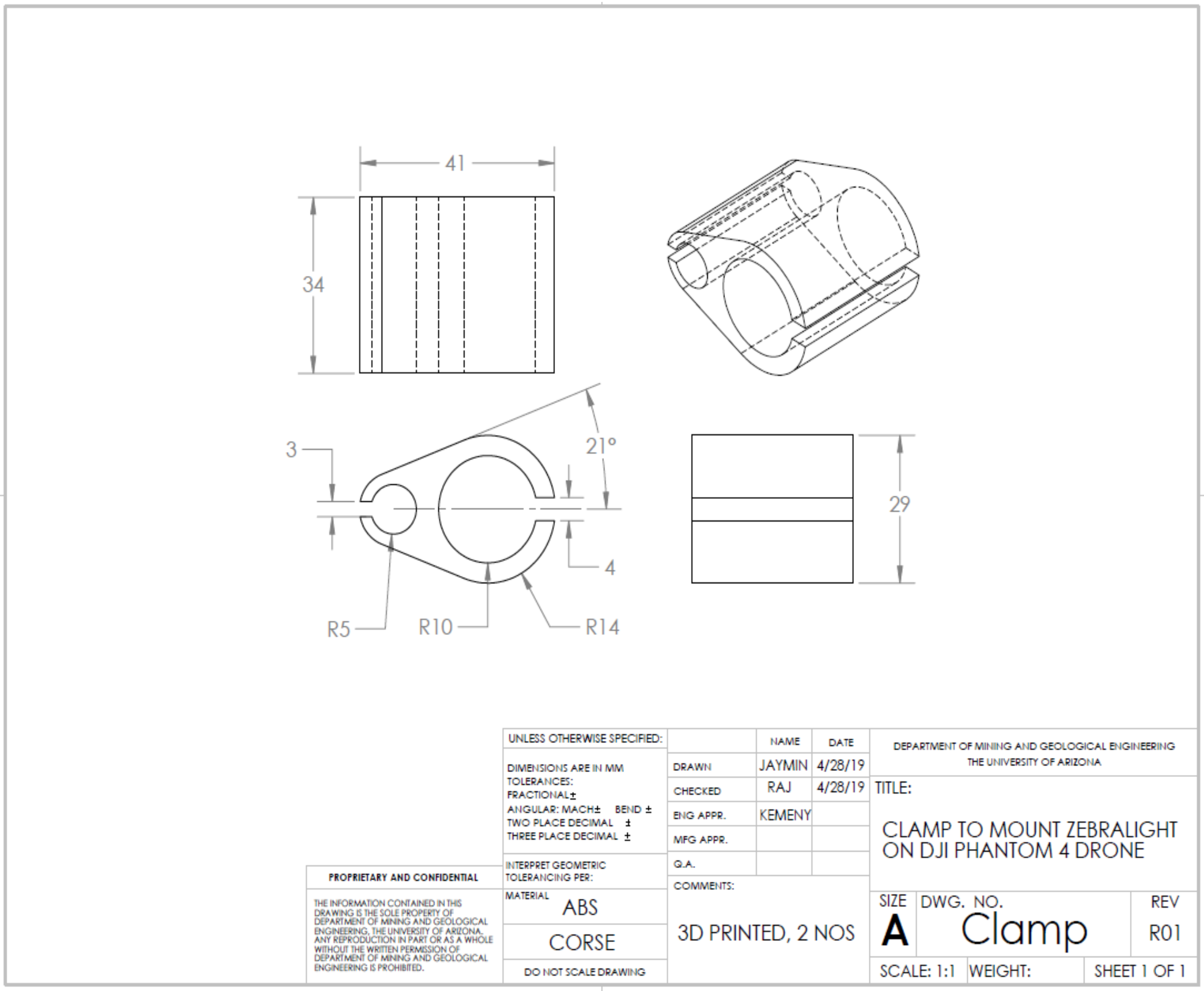
3. Another issue with the use of drones in an underground mine is the navigation problem. Mining stopes and tunnels are big and navigation through them is difficult. Once the pilot loses line-of-sight, the chance of a drone accident increases. However, this problem can be solved with the use of different computer algorithms. One such algorithm is the SLAM (Simultaneous Localization and Mapping) technique, which allows the drone to digitize a large environment and constructs a map in real time. Despite incomplete information about the trajectory through the atmosphere, SLAM will navigate the drone in any situation and assist with optimal image acquisition. SLAM has been tested with LIDAR scanners mounted on a drone but not with photogrammetry. This is a possible future research area for drones.

4. The drone point cloud can be used to calculate additional geotechnical properties that were not considered in this research, including fracture roughness, fracture spacing, rock mass classification systems (GSI, RMR, etc.), and other geotechnical information. Some of these properties such as fracture roughness will not be possible until point clouds with a higher resolution can be produced.

5. At the University of Arizona, the drone can be used in the future to explore difficult-to-reach and unsafe parts of the SX Mine. This will allow a more complete inventory of underground excavations at the SX mine, including information on geology, geotechnical conditions, and detailed surveying.

APPENDIX A: LIST OF FIGURES

APPENDIX B: DESIGN SPECIFICATION OF CLAMP FOR MOUNTING ZEBRALIGHTS ON THE DRONE

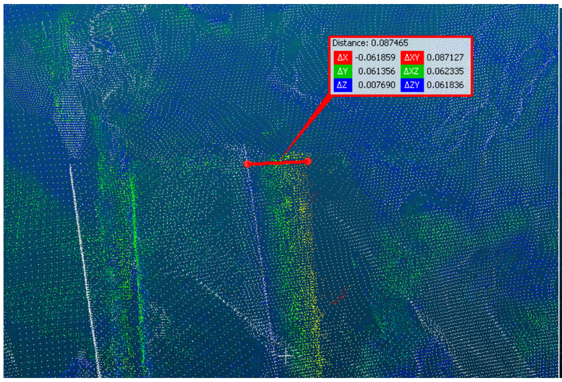


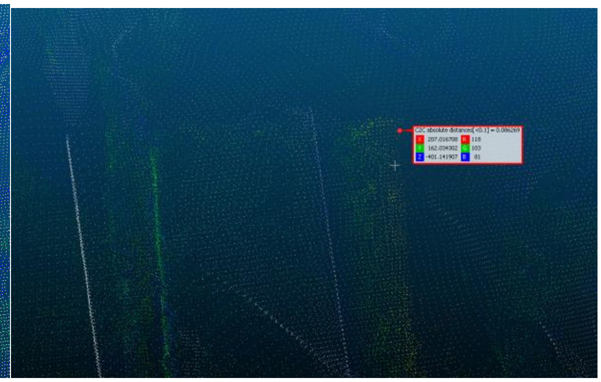
APPENDIX C: DETAILS OF THE TEST FLIGHT

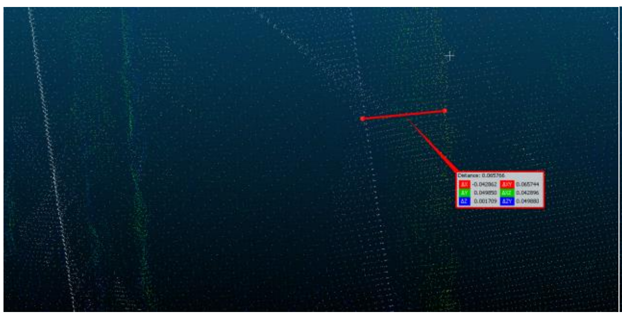
FLIGHT NUMBER	LOCATION OF TEST FLIGHT	LIGHT SOURCE	DATE PERFORMED	NUMBER OF IMAGE CAPTURED	PROCESSING PLATFORM	NUMBER OF POINTS GENERATED	POINT DENSITY	IMAGE SCALE
1	SX MINE, SURFACE	NATURAL LIGHT	9/14/2018	N/A		N/A	N/A	N/A
2	SX MINE, SURFACE	NATURAL LIGHT	9/15/2018	N/A		N/A	N/A	N/A
3	SX MINE, SURFACE	NATURAL LIGHT	9/21/2018	64	PIX4D CLOUD PLATFORM	4	OPTIMAL	HALF IMAGE SIZE
4	SX MINE, DECLINE	NATURAL LIGHT	9/21/2018	21	PIX4D CLOUD PLATFORM	2	OPTIMAL	HALF IMAGE SIZE
5	SX MINE, IN FRONT OF THE ADIT	NATURAL LIGHT	9/21/2018	64	PIX4D CLOUD PLATFORM	4	OPTIMAL	HALF IMAGE SIZE
6	SX MINE, DECLINE	ARTIFICIAL LIGHT, 4 PIECE OF 500W, 102 VOLT HALOGEN LIGHT	9/28/2019	26	PIX4D CLOUD PLATFORM	1	OPTIMAL	HALF IMAGE SIZE
7	PEPPER SAUCE CAVE	ZEBRA LIGHTS USED BUT NOT MOUNTED ON THE DRONE	10/14/2018	50	PIX4D CLOUD PLATFORM	N/A	OPTIMAL	HALF IMAGE SIZE
8	SX MINE, DECLINE	MICRO LED LIGHTS USED	11/2/2018	3	PIX4D CLOUD PLATFORM	N/A	OPTIMAL	HALF IMAGE SIZE
9	SX MINE, IN FRONT OF THE ADIT	ZEBRALIGHTS	11/16/2018	34	PIX4D CLOUD PLATFORM	2	OPTIMAL	HALF IMAGE SIZE
10	SX MINE, 100 FEET LEVEL	ZEBRALIGHTS	1/31/2019	N/A	PIX4D CLOUD PLATFORM	N/A	OPTIMAL	HALF IMAGE SIZE

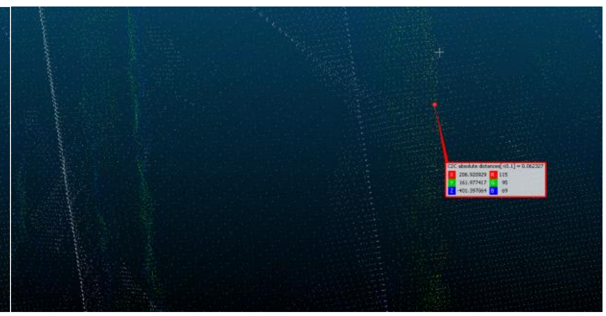
FLIGHT NUMBER	LOCATION OF TEST FLIGHT	LIGHT SOURCE	DATE PERFORMED	NUMBER OF IMAGE CAPTURED	PROCESSING PLATFORM	NUMBER OF POINTS GENERATED	POINT DENSITY	IMAGE SCALE
11	SX MINE, 100 FEET LEVEL	ZEBRALIGHTS	2/5/2019	164	PIX4D CLOUD PLATFORM	43	HIGH DENSITY	ORIGINAL IMAGE SIZE
12	SX MINE,SURFACE	NATURAL LIGHT	3/16/2019	71	PIX4D CLOUD PLATFORM	4	OPTIMAL	HALF IMAGE SIZE
13	ROCK MECHANICS LAB, MINES BUILDING	ZEBRA LIGHTS (AUTO MODE)	3/31/2019	47	DESKTOP PROCESSED	38	HIGH DENSITY	ORIGINAL IMAGE SIZE
14	ROCK MECHANICS LAB, MINES BUILDING	ZEBRA LIGHTS(MANUAL MODE)	3/31/2019	36	DESKTOP PROCESSED	32	HIGH DENSITY	ORIGINAL IMAGE SIZE
15	SX MINE, IN FRONT OF THE ADIT	ZEBRALIGHTS(AUTO MODE)	4/3/2019	21	PIX4D CLOUD PLATFORM	7	HIGH DENSITY	ORIGINAL IMAGE SIZE
16	SX MINE, IN FRONT OF THE ADIT	ZEBRA LIGHTS(MANUAL MODE)	4/3/2019	31	DESKTOP PROCESSED	18	HIGH DENSITY	ORIGINAL IMAGE SIZE
17	SX MINE, SURFACE	NATURAL LIGHT(AUTO MODE)	4/6/2019	33	DESKTOP PROCESSED	23	HIGH DENSITY	ORIGINAL IMAGE SIZE
18	SX MINE, SURFACE	ZEBRALIGHTS	4/22/2019	134	DESKTOP PROCESSED	8	OPTIMAL	HALF IMAGE SIZE

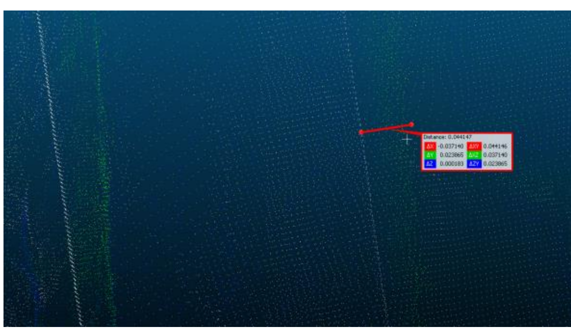
APPENDIX D: CHANGE DETECTION VALUES AND IMAGES

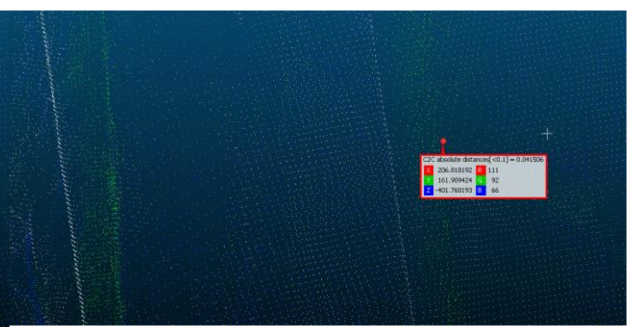


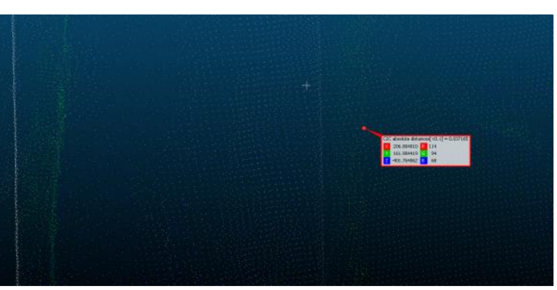


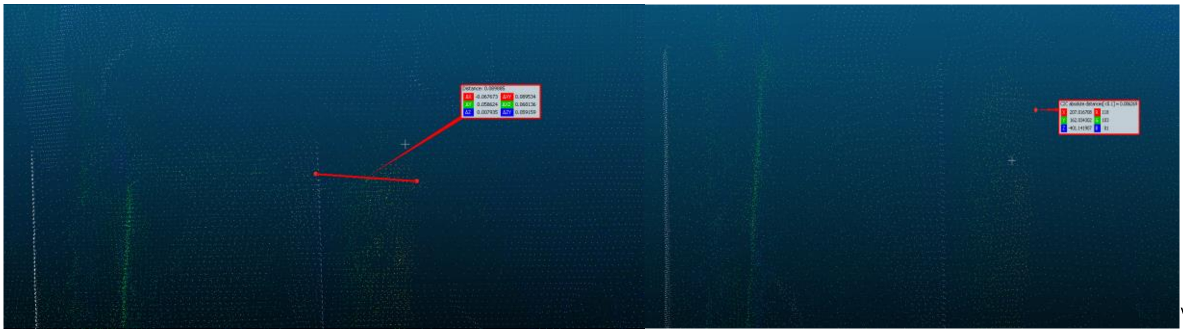












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Measurment Number	Change detection measured manually Δ	Change detected measured automatically Δ
1	0.089885	0.086269
2	0.0874658	0.086269
3	0.065766	0.062327
4	0.044147	0.041506
5	0.031911	0.037165

APPENDIX E: LIST OF TABLES

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