SME Annual Meeting
Feb. 24 - 27, 2018, Denver, CO

Preprint 19-095

A COMPARISON OF LASER SCANNING AND PHOTOGRAMMETRY IN AN UNDERGROUND LIMESTONE MINE

R. Bishop, Virginia Tech, Blacksburg, VA
J. Monsalve, Virginia Tech, Blacksburg, VA
J. Baggett, Virginia Tech, Blacksburg, VA
A. Soni, Virginia Tech, Blacksburg, VA
N. Ripepi, Virginia Tech, Blacksburg, VA

ABSTRACT

Technology plays an ever-increasing role in improving the safety and efficiency of mining operations. Laser scanning and photogrammetry are two useful methods for capturing 3D digital representations of real world objects. While both technologies have been applied to the mining industry in numerous ways, the practical applications in an operating underground limestone mine has been tested for this paper, including for visualization and site characterization. Each technology is capable of creating highly detailed geospatial point clouds, but are all point clouds created equal? This paper presents a comparison of a laser scan and photogrammetry of a limestone pillar and addresses the strengths and limitations of each method for creating digital models of operating underground limestone mines.

INTRODUCTION

The United States crushed stone business is a ~$14 billion per year industry representing 1,430 companies which operate 3,782 mining operations across the 50 states. In 2017 alone, 1.33 billion tons of crushed stone was produced with 76% used predominately for road construction and repairs, but also for the production of cement, lime, chemical and agricultural uses. Over 70% of domestic crushed stone producers source their material from limestone and dolomite deposits, with currently only 82 mines (2%) operating underground (USGS, 2018).

Underground mining requires a different technical skillset, and poses great challenges for production that must be both safe and economical. Therefore, there are many risks that an operation must mitigate in order to produce underground limestone. Some of the challenges in underground limestone mining involve geological hazards that are unique to the rest of the industry. The geologic features such as faults and weaknesses can be difficult to assess in a production environment (NIOSH, 1998). The consequences of failure due to improperly designed underground mining ground support systems, such as from a roof failure, are not only life threatening for the miners themselves, but can easily shut down an entire mining operation.

Underground limestone mines in the eastern U.S. have become more common over the past decade and typically there is less underground experience resulting in a need for more engineering controls. Over the past ten years 40% of underground mining fatalities were caused by ground control issues related to ground collapses. Over the same period the underground stone mining industry has had the highest fatality rate in four of those ten years, more than any other mining sector (MSHA, 2016).

Photogrammetry and laser scanning are technologies that can help characterize rock mass discontinuities and joint sets, as well as help monitor ground control. They have also proven useful for 3D mapping. These technologies have the potential to help mine operators better characterize ground failure mechanisms and visualize hazards.

Overview – Laser Scanning

Three-dimensional laser scanning, or LiDAR, is a remote imaging method which can collect 3D point coordinates of a scanned scene with high resolution and accuracy. It also helps with detailed mapping of the structural features present in underground workings, not only by increasing the safety and precision over traditional surveying with automated scans, but also by reducing time while mapping (Adu-Acheampong et al, 2013). It is well-suited for underground use as it requires no lighting to complete a scan. Software such as Maptek's I-Site program are designed to process the point clouds obtained from laser scanning, which can be used for geotechnical analysis in underground limestone mining operations (Monsalve et al, 2018). In these applications, laser scanning has also been shown to be effective in determining the volumetric changes when measuring rib displacement, and particularly suited for determining sloughage off of a surface (Slaker, 2015). The 3D laser scan can be seen below in Figure 1.

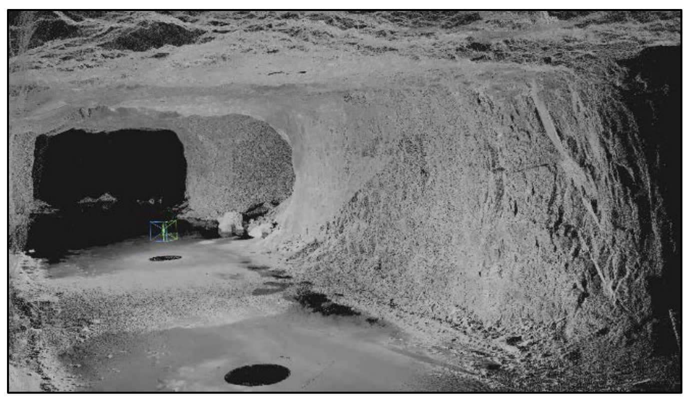

Figure 1. Three-dimensional point cloud of the face of subject limestone pillar from laser scanning.

Overview - Photogrammetry

Photogrammetry is a method of using photographs taken from different locations to derive measurable spatial relationships within the subject. Most mining operations in the USA presently have access to a digital camera in addition to a computer capable of the basic processing requirements to compile a photogrammetry model. However, photogrammetry it is not without unique challenges in an underground mine environment. Photography requires adequate light to record photographic data. While the low light environment encountered in an underground mine can be offset with a camera flash and/or supplementary lighting as well as longer exposure times, dust, moisture and the large cavernous openings in underground limestone mines can make it difficult to get quality surveys. Figure 2 illustrates the use of photogrammetry to model the perimeter of the subject pillar, the face of which will be used in comparison to the laser scan presented in Figure 1.

Figure 2. Three-dimensional rendering of subject pillar using photogrammetry.

EQUIPMENT AND METHODOLOGY

Photogrammetry

While photogrammetry can be performed with virtually any camera, equipment selection is important for efficient quality surveys in large opening underground mines such as room & pillar limestone mines. For this comparison test, a Canon 6D full-frame digital single-lens reflex (DSLR) camera was paired with a Sigma 35mm f1.4 prime lens. This camera contains a 20.2 megapixel CMOS sensor capable of 5472 x 3648 pixel images and a wide ISO sensitivity range from 50 – 102,400.

A more important consideration than the camera body, is the choice of camera lens. The focal length of a camera lens refers to the optical distance between the lens and camera image sensor and is the specification that describes if a lens provides magnification (zoom) or a wider angle view. Figure 3 below illustrates the effect of focal length on field of view for a full-frame camera with various focal length lenses.

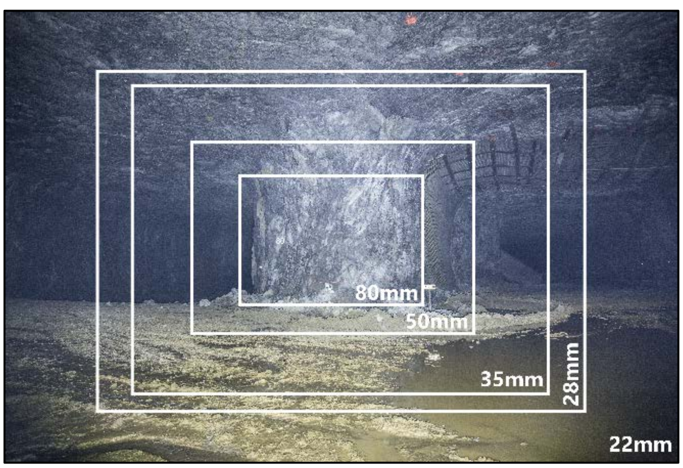

Figure 3. Effect of focal length on field of view.

On a full-frame camera, 50mm is regarded as the focal length equivalent to what our eyes see, whereas 35mm is considered the initial range of wide angle lenses and 80mm would be considered a zoom lens. A crop-sensor camera paired with a 35mm lens is similar to the field of view of a full-frame camera with a 50mm lens and a 50mm lens on a crop-sensor camera has a similar field of view as an 80mm lens on a full-frame camera (Vorenkamp, 2015).

Photogrammetry requires overlapping images in order for the processing software to calculate a point cloud. 60% overlap is the general guideline recommended between images (Agisoft, 2018). In order to save time and simplify the collection of photographs, the height of the subject pillar should fill the camera frame, such that the survey can be performed laterally along the face of the pillar.

The subject pillar in our test measured approximately 13 meters in height during the first phase of mine development when the survey was performed. With a 13 meter entry between the pillar face and the rib, the distance that away from the subject to make photographs is a limiting factor. In this survey, a 35mm lens allowed for the full height of the pillar to fit vertically in the camera frame while also allowing for adequate lighting mounted alongside the camera tripod to produce a consistently illuminated subject within the field of view of an individual photograph as seen below in Figure 4.

Figure 4. Photogrammetry survey of mine pillar.

Lighting is a very important consideration for photogrammetry surveys in underground limestone mines. After much trial and experimentation, a pair of 3-inch by 3-inch diffused flood beam 20-watt LED's were chosen and powered by a 11,000 milliamp-hour 12-volt lithium ion rechargeable battery pack. This configuration allowed for consistent lighting during the survey and clear images with the camera set to an f-stop of f/6.7 with a 2 second exposure at ISO 1000.

Laser Scanning

The laser scan was performed with a Faro Focus^{3D} laser scanner. According to the manufacturer, the instrument is capable of 360^{o} scanning from 0.6 meters up to 120 meters with a step size of 0.009^{o}. The unit is capable of capturing up to 976,000 points per second with a vertical field of view of 305^{o} (Faro, 2013).

The laser scanner was mounted to a tripod during the survey in two locations located 13 meters apart corresponding with the approximate entry width in front of the pillar. These locations are indicated by the two circular gaps in the point cloud floor in Figure 1 and by the tripod icons in the map below in Figure 5.

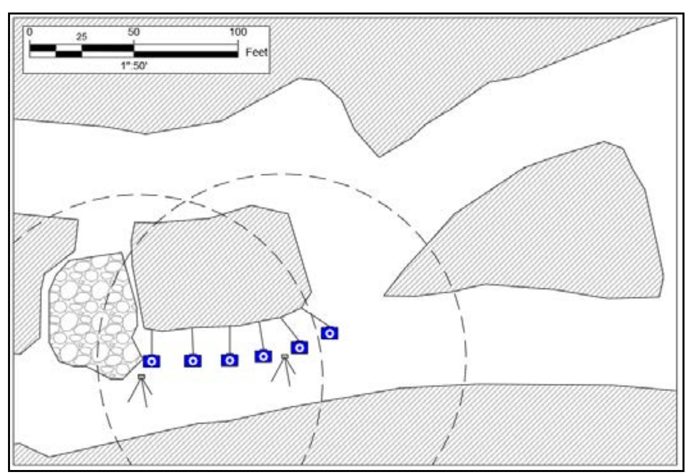

Figure 5. Survey overview map (icons not to scale).

The laser scanning process was mostly automated. Reference objects were placed between the two scan locations. The two separate scans were then merged into one point cloud by the alignment of the reference objects. The scan settings were specified on the built in menu at ¼ resolution and started with the press of a touchscreen icon.

In less than 6 minutes per station, the device automatically rotated in all directions collecting geospatial point locations from the reflection of the laser onto the surrounding surfaces. Figure 6 shows the laser scanner on the tripod in preparation for the first scan of the mine pillar.

Figure 6. Laser scan of limestone mine pillar.

DATA PROCESSING & ANALYSIS

Post-processing is typically the most time intensive portion of a photogrammetry survey, particularly on higher quality settings. The photogrammetry survey processing was completed in Agisoft PhotoScan Standard (version 1.4.4) on a Windows 10 laptop with an Intel i7-5500U processor @ 2.40 GHz, 16 GB RAM and GeForce 840M graphics. Camera matching and alignment took 2 minutes 50 seconds and 44 seconds, respectively. The dense point cloud consisted of 44,865,485 points and was reconstructed using ultra high quality settings and aggressive depth filtering which required 3 hours 21 minutes to generate the depth maps and 2 hours 28 minutes to generate the dense cloud. At this stage the model was exported as an *.E57 point cloud file for comparison with the laser scan data.

The laser scan data was processed and aligned with the Faro Scene software. Processing required 2 minutes 34 seconds on the same computer. The laser scans acquired 21,646,505 points between the two full 360° surveys on the ¼ resolution setting. It was also exported as an *.E57 point cloud.

Both photogrammetry and laser scan point clouds were then imported into CloudCompare (version 2.10-alpha) for analysis. CloudCompare is a free, open-source, 3D point cloud processing program that allows for comparison of two dense point clouds (CloudCompare, 2018). After importing, the laser scan point cloud was already scaled and registered, however the photogrammetry point cloud required resizing and alignment / registration with the laser scan. The laser scan point cloud was then segmented to reduce the area scanned to the pillar face for comparison. The laser scan and photogrammetry point clouds can be seen individually below in Figure 7.

The quality of point clouds from both laser scanning and photogrammetry are more than sufficient to map discontinuities in geotechnical software packages such as Maptek I-Site. The additional color information provided by the photogrammetry model can be helpful to better visually identify mineral variation and also provide a more photorealistic rendering of the mine area for visualization. Figure 8 below is a distance comparison from CloudCompare between the laser scan point cloud and the photogrammetry point cloud on a point by point basis, including a frequency distribution.

In the chart and image of Figure 8, CloudCompare revealed that the greater deviation between scans occurred at the corners of the pillar corresponding to the edges of the surveys. Both surveys had more dense point clouds in the center of the pillar where there were more overlapping data points. The photogrammetry survey had more overlapping images at the center and the two laser scan stations converged point clouds at the middle of the pillar.

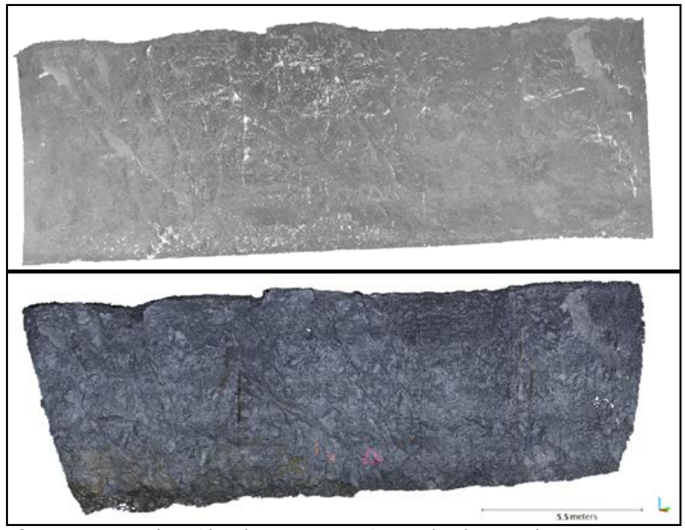

Figure 7. Point Clouds – Laser Scan (top) vs Photogrammetry (bottom) from CloudCompare.

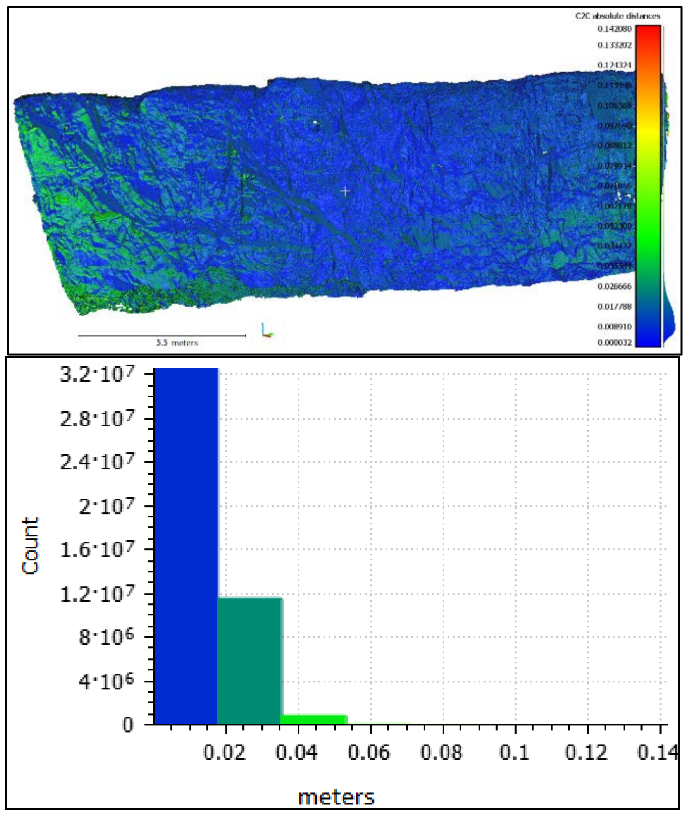

Figure 8. Distance error analysis (CloudCompare).

The results support the quality of both scans and the ability to merge both point clouds when required. For example, if a mining operation does not own their own laser scanner, but may have had a consultant scan part of the mine, they could generate a new point cloud using photogrammetry to append the laser scan with additional information. In addition, texture detail from the photogrammetry model can be overlaid on the laser scan point cloud to provide more photorealistic detail of the working face or mine pillars to better visualize a short term mine plan and/or ground control design.

ADVANTAGES & LIMITATIONS

Laser Scanning

Laser scanning has several advantages over photogrammetry in an underground limestone mine. A laser scanner is able to acquire a detailed point cloud of the full surrounding area around the station, seamlessly merging the sides, roof and floor. This was found to be a more difficult task with photogrammetry as it requires overlapping images that become more difficult to orientate when capturing overhead. The laser scanner also performs very well in a dark environment, whereas photogrammetry needs adequate lighting to ensure proper camera focus and sharp images. Also, point clouds from the laser scanner are already scaled when they are generated, whereas photogrammetry needs reference objects for scaling after processing. It also has the advantage of being quicker to process after a large survey.

Photogrammetry

Photogrammetry has the advantage of having a lower upfront cost for equipment, much of which might already be owned by the mining operation. If a camera, lens, battery or light needed to be replaced, there are many available options on the market. The software for creating photogrammetry models is constantly advancing, as is computing power. However, one of the limitations of photogrammetry over laser scanning is processing time relative to laser scanning for complex scenes. Small surveys can be performed and processed quickly, but larger, more expansive surveys allow more room for user error during the survey and more processing time. Good lighting is essential for good results in photogrammetry. Thus, some areas such as the upper portion of limestone pillars and the roof, can be over 30 meters overhead and be challenging to illuminate. Also some areas may have limited access, such as under unsupported ground and open karsts, which may impact the completeness of a survey.

Merging Both Technologies

Both photogrammetry and laser scanning have their unique advantages and disadvantages, however opportunity exists to enhance the quality of each survey by combining them. Figure 9 shows the face of the pillar (on the right hand side) merged onto the 360^{o} laser scan using RealityCapture software (Capturing Reality, 2018). The detailed color texture map from photogrammetry provides added detail and the laser scan provides orientation. This approach is very useful for visualization and can be used for training exercises in a photorealistic virtual reality (VR) environment.

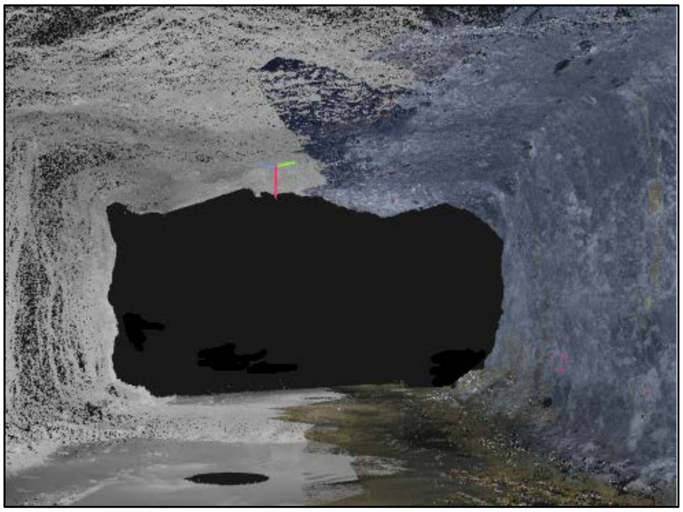

Figure 9. Merged laser scan (L) + photogrammetry (R).

CONCLUSION

Underground limestone mining is a growing segment of the U.S. mining industry, which is associated with inherent roof fall hazards that must be controlled and managed during the life of mining. The industry faces many risks due to geological hazards with major consequences of failure, including worker injuries, production delays / setbacks, miner safety, lost reserves, flooding and unanticipated roof control costs, amongst many others.

The methodologies and techniques for monitoring underground limestone mine workings, such as photogrammetry and laser scanning, show great promise as equipment, computational power, and software continues to advance. The survey detail both technologies can provide can help operations be proactive with risk management and ground control design and monitoring. It was found in this study that both point clouds compare favorably in the level of detail that can be used for mapping geological structures / discontinuities as well as a base for ground control design using the scans as as-built surveys.

With limestone ore being a relatively low value commodity compared to coal and precious metals mining, cost and budget considerations when trying to implement new technologies can be a major obstacle for companies. However, using risk assessment concepts to quantify the consequences of failure of reacting to ground failures after they occur rather than using the best available monitoring and modelling techniques, a compelling argument can be made for maintaining a level of acceptable service in underground limestone mine ground control by preventing roof and pillar failures.

ACKNOWLEDGMENTS

Financial assistance for this work was provided by the National Institute for Occupational Safety and Health (NIOSH) under contract number 200-2016-91300.

REFERENCES

1. Adu-Acheampong, A., Byers, T., Dodd, M., Basson, F., Bartlett, M., & Duran, J. (2013). An Overview of Imaging Technologies at Newmont Mine Sites. SME Annual Meeting. Denver: SME.
2. Agisoft. (2018, October 31). PhotoScan Software. Retrieved from Agisoft LLC.: http://www.agisoft.com/
3. Capturing Reality. (2018, October 31). RealityCapture Software. Retrieved from Capturing Reality S.R.O.: https://www.capturingreality.com/
4. CloudCompare. (2018, October 31). CloudCompare Open Source Project. Retrieved from: https://www.danielgm.net/cc/
5. Faro. (2013). Faro Focus^{3D} – Features, Benefits & Technical Specifications. Retrieved from Faro: https://www.faro.com/
6. Maptek. (2018, October 31). I-Site Software. Retrieved from MAPTEK Pty Ltd.: https://www.maptek.com/products/i-site/
7. Monsalve, J., Baggett, J., Bishop, R., & Ripepi, N. (2018). Application of Laser Scanning for Rock Mass Characterization and Discrete Fracture Network Generation in an Underground Limestone Mine. 37th International Conference on Ground Control in Mining. Morgantown: ICGCM.
8. MSHA. (2016). Summary of Fatal Accidents at Metal/Nonmetal Mines with Preventative Recommendations. Washington D.C.: U.S. Department of Labor.
9. NIOSH. (1998). Innovative Hazard Recognition Training for Underground Limestone Miners. Pittsburgh: NIOSH.
10. Slaker, B. (2015). Monitoring Underground Mine Displacement Using Photogrammetry and Laser Scanning. Blacksburg: Virginia Tech.
11. USGS. (2018). Mineral Commodity Summaries. Washington D.C.: U.S. Department of the Interior, U.S. Geological Survey.
12. Vorenkamp, T. (2015). Understanding Crop Factor. Retrieved from BH Photo Video: https://www.bhphotovideo.com/explora/photography/tips-and-solutions/understanding-crop-factor