3D TIME-OF-FLIGHT CAMERA FOR SURVEYING REMOTE CAVITIES MINED WITH A JET BORING SYSTEM

*C. A. Ingram
Queen's University and Cameco Corporation
2121-11th Street West
Saskatoon, Canada S7M 1J3
*(*Corresponding author: Carolyn_Ingram@cameco.com)*

J. A. Marshall
The Robert M. Buchan Department of Mining
Queen's University
Goodwin Hall, 25 Union Street
Kingston, Canada K7L 3N6

3D TIME-OF-FLIGHT CAMERA FOR SURVEYING REMOTE CAVITIES MINED WITH A JET BORING SYSTEM

ABSTRACT

The Cigar Lake ore body is a high-grade uranium deposit situated within water-saturated sandstone. In order to extract the uranium ore remotely, ensuring minimal radiation dose to workers, and also to access the ore from stable ground, the Jet Boring System (JBS) was developed. This method of mining involves drilling a pilot hole up through a frozen ore body and utilizing a high-powered water jet to mine out cavities. During the mining process an ultrasonic sensor will be used to provide feedback to the operator, who is located beneath the ore body, as to the dimensions of the cavity. However, more precise data is required to determine final shape, volume, and location of the cavity for mine planning purposes. Selecting a device that will provide sufficient range data in the challenging environment will be vital to optimizing the mining process. Major issues include fog build up and flying debris during mining, and an environment that is wet, dark, and cold.

A test cavity has been designed and constructed at the Saskatchewan Research Council (SRC) so that a study comparing three different technologies, as prospective candidates for the survey system, can be conducted. The devices being evaluated include a Senix ultrasonic sensor, an MDL Cavity Auto-Scanning Laser System (C-ALS), and a MESA Time of Flight (ToF) camera. The ultrasonic sensor is known to provide range data in foggy conditions but has low accuracy. The C-ALS has been developed for surveying remote cavities but is expensive and does not provide reliable data in fog. The ToF camera provides a high volume of data in a short time period, with potential to provide accurate information in extreme conditions, but has not been tested in a mine cavity application. Iterative closest point (ICP) registration is applied in an attempt to create a 3D point cloud from the scan data and to also compute rotation and translation of the ToF camera. This paper presents an overview of the challenges involved in conducting a survey within a JBS mined cavity, the analysis used to determine the suitability of each device, and the data collected from the test cavity.

KEYWORDS

ToF camera, C-ALS, Point Cloud Library, ICP, Registration, Cavity Survey, Jet Boring

INTRODUCTION

At Cigar Lake, the Jet Boring System (JBS) was developed to access a high-grade uranium body that is situated in water-saturated sandstone. Before mining begins, the ore body and surrounding rock is frozen to strengthen it and also to prevent inflows. A pilot hole is then drilled up through the ore body and cased, providing a path for the jet string and nozzle. The jetting begins at the top of the ore body and progresses downwards in periods, as the jet rotates and traverses about its axis, until the lower limit of the ore body is reached. As the cavity is jetted, the ore slurry falls through the annulus of the pilot hole casing and jet pipe and into a slurry storage tank before being pumped to the run of mine (ROM) area. From here, further processing of the slurry occurs underground and is finally pumped to surface (Cameco Corp., 2010).

The purpose for the cavity survey, which will take place between periods of jetting, is to provide feedback to the operator, who is located beneath the ore body (Fig. 1), indicating the dimensions of the cavity. While mining, it is important to achieve maximum recovery while preventing ground instability that may be caused by too large of a cavity. Following the mine plan, the operator will need to know if it is necessary to focus the jet on a particular area within the cavity, change the jetting parameters, or to cease mining. Additionally, the final location of the cavity and its dimensions are required in order to update resource estimates and production values. The volume of required backfill can be also be determined if the cavity shape is known. Knowledge of the JBS's performance and the ability to optimize procedures to ensure efficient maximum recovery are necessary for a successful mining program. The challenge is to find an appropriate technology that can acquire reliable data within the extreme cavity environment.

CIGAR LAKE REMOTE CAVITY SURVEY

At Cigar Lake, the original goal was to "precision mine" each ore cavity. The first prototype contained several features, including a laser rangefinder, an IR target detector, IR LEDs for camera illumination, and sapphire lenses for the laser, video, and target detector. With the field testing described below, a better knowledge of the operating conditions was obtained, and changes to the original specifications and prototype were made. Field testing of prototype cavity survey systems (CVSS) took place in 2000 from April through November (Wacker, 2001).

The first set of tests was conducted in a vertical culvert in an underground raise, with simulated rock conditions similar to those expected during a typical mining situation. Through the process, it was found that a less precise mining method could be pursued, and thus, the inclusion of components such as the target detector and video camera were deemed unnecessary. With the system simplification, it was possible to move the laser range finder higher above the jetting nozzle further from the debris that may be launched as a result of jetting. The next phase of testing took place in frozen waste rock conditions below the ore body. With water being sprayed in a frozen environment, a resultant dense fog ensued and caused the laser rangefinder cavity survey system to be rendered inadequate. Some effort was made in an attempt to eliminate or reduce the fog, but this was unsuccessful.

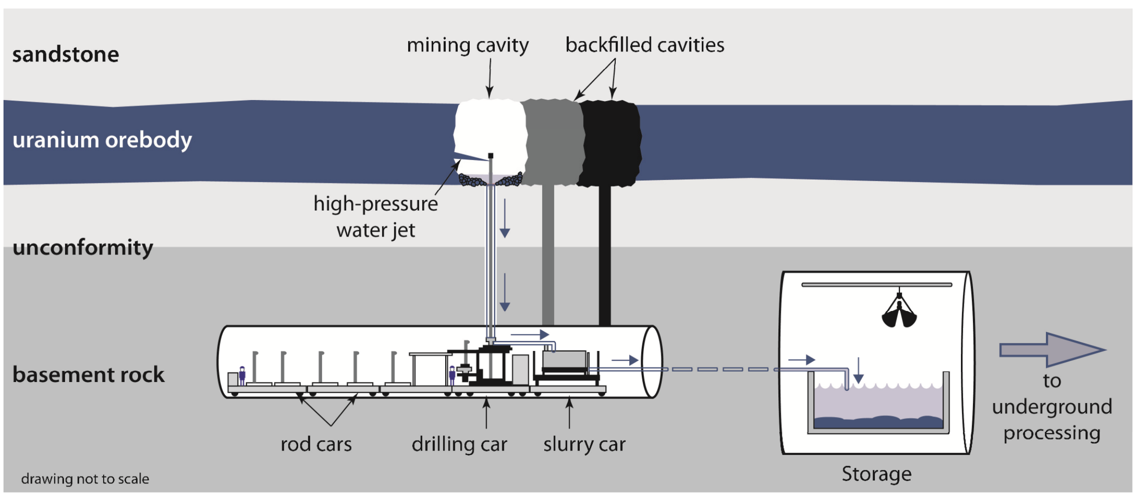

Figure 1 – JBS mining schematic for Cigar Lake (image: Cameco Corporation)

An ultrasonic sensor was subsequently chosen as the replacement for the laser rangefinder due to its off-the-shelf availability, low cost, and, most importantly, the ability of the signal to penetrate the fog. During testing in the ore body, it was discovered that significant cavity wall erosion occurred above the jet as mining progressed downward and, as a result, it was determined that a final survey of the cavity, prior to backfilling, would be required. Preferably, this survey would be completed as quickly as possible after jetting is complete, before any additional sloughage occurred. Since the ultrasonic sensor did not provide a high enough level of precision and resolution, the decision was made to again employ the use of a laser rangefinder. The post cavity survey would be in addition to the ultrasonic survey, which would still be completed between periods of jetting to provide feedback to the operator. Through the process of field testing, it was found that the Cigar Lake cavity shape could be approximated by a cylinder of height ranging from 3 m to 15 m and a diameter ranging from 3 m to 5 m, with the cavity surface comprising of dark, wet, frozen uranium ore.

In 2005, a review of current technology was conducted by the Saskatchewan Research Council (SRC), in which an MDL Cavity Auto-Scanning Laser System (C-ALS) (MDL, 2013) was identified at the most viable technology for the post cavity survey system (SRC, 2005). It was small enough to inside the backfill pipe (5" inner diameter) and was equipped with a suitable deployment method and data processing software. For the interim cavity survey system, in 2006, several ultrasonic range sensors were tested in lab, where the Senix ToughSonic TSPC-30S1, demonstrated the best performance for the Cigar Lake application (SRC, 2006).

Survey Sensor Evaluation

Armed with the combination of the ultrasonic sensor and a laser scanning system, it would seem the bases would be covered; Senix ultrasonic to provide approximate range data to the operators during the jetting process and the C-ALS to provide final, accurate, dimensional data for mine planning. However, might it be possible that a single technology could provide sufficiently accurate data during the jetting process? This would be ideal, having the potential to result in significant time and cost savings. With an investigation into technologies currently available, the ToF camera was identified as possessing sufficient characteristics to warrant an evaluation, testing it for suitability within the Cigar Lake cavity survey application. Each range finding device uses the time-of-flight principle in which the time for a signal to travel from source to target, where it is reflected, and back is measured. The distance to the target can be calculated based on knowledge of signal speed. A brief description of each sensor's properties and their advantages and disadvantages follows.

An ultrasonic signal is a longitudinal, mechanical wave where the accuracy in range measurement relies on knowing the speed of sound in the particular medium. The geometry of the area surrounding the target and the angle of incidence to the target will also have an effect on the acquired measurements. It may be possible for the echo to be reflected away from the transducer and/or be reflected at multiple points before returning to the receiver. An ultrasonic signal has a relatively wide beam width and, if it were to strike an area composed of several distances, it would be impossible to resolve the smaller target component of the returned signal. A smoothed average of the various distance measurements is currently used for viewing data. This should provide a reasonable amount of information for the JBS operators to make a decision whether certain areas require further jetting.

A laser device can emit a single light beam comprised of a high degree of coherence and very narrow width. Thus, it is possible to obtain very accurate measurements from a laser with high angular resolution; however, it is also highly dependent on the visibility within the medium and the target's properties. In clear air, the attenuation is minimal but, for mining applications, where dust particulates and fog are often present, the attenuation can be severe. Spurious readings may occur as photons are returned prior to the beam reaching its intended target. The target itself can also have an effect on the quality of the signal returned. On a smooth, shiny or wet surface, specular reflection may occur and depending on the angle of incidence, the reflected beam may not be returned to the receiver. There is also potential for absorption of the laser signal on the dark surfaces. The fog created within a cavity during jetting, as discovered during testing in 2000, will be a limiting factor in how soon the post cavity survey occurs once jetting is complete.

A time-of-flight (TOF) camera operates with the use of an infrared signal source. The MESA Imaging SwissRanger (SR4030) was chosen for the Cigar Lake application due to its small size, weight, and commercial availability (MESA Imaging). It uses a CCD/CMOS imaging sensor where the phase delay of the recovered signal is used to calculate target distance. From the single pixel values on the imaging sensor, a 176×144 pixel depth map is computed, totalling 25,344 range points per frame in a single image acquisition. Additionally, a conventional black-and-white image can be obtained from the offset of the signal and its amplitude provides a measure of the quality of the distance information (Oggier, et al.). Current reviews claim that it is foreseeable that ToF cameras will replace previous solutions, or alternatively complement other technologies, in many areas of application (Foix, Alenya, & Torras, 2011).

It can been seen in Table 1 that the SwissRanger device is the fastest device, obtaining up to 50 sets of data within the camera's field of view every second, where the laser only obtains 250 data points per second. The data from the laser is plotted as in real time but would take over a minute to collect and display what the MESA ToF can obtain in 1/50th of a second. Also, this data from the ToF camera can be viewed as a conventional black and white image, which is especially useful for a visual representation of the cavity. It is expected that IR signals from the ToF camera will be affected in a similar manner to the laser in the fog and on the dark, wet surfaces. However, since a substantially higher number of points can be obtained in a short period of time, it may be possible to filter the spurious readings, and be left with a suitable image for interpretation. If this is shown to be the case, it may be possible to use the ToF camera sooner than the C-ALS in foggy conditions and as a supplement or even replacement for the ultrasonic sensor.

Table 1 – Comparison of Survey Devices

	Senix ToughSonic TSPC-30S1	MDL MKIII C-ALS	MESA SR4030 ToF Camera
Cost	Low	High	Medium
Data Acquisition rate	20 points/s	250 points/s	50 frames/s
Grayscale Image	No	B&W video	Yes
Packaging	IP68	IP67	IP67
Fog/Water conditions	Good	Poor	Unknown
Closed Space	Unknown	Good	Good
Cavity Surface Reflectivity	Unaffected	Unknown	Unknown
Range Accuracy	0.2% of range	+/- 5 cm	+/- 15 mm
Development Stage	Custom System	Commercial	Required

With regards to the mechanical composition of the sensors, laser systems generally employ several moving parts. The SwissRanger does not. Often with increased complexity, comes increased maintenance, and since the cost of the C-ALS is already substantially higher than the SwissRanger, this characteristic offers another significant advantage. It is known that in ideal conditions, laser systems have outperformed TOF cameras (Cui, Schuon, Chan, Thrun, & Theobalt, 2010) for the purpose of very detailed 3D imaging, but for the Cigar Lake application, the TOF camera data could show to be more accurate and reliable. In fact, according to data sheets, the range accuracy of the SwissRanger is superior to the C-ALS.

A major advantage of the C-ALS laser system is that it is a complete off-the-shelf system, equipped with application software, integrated pitch and roll sensors, and a deployment method. The C-ALS deployment method will not be used at Cigar Lake since a custom system was developed for deployment on the JBS through backfill pipes. For the ToF camera, it is predicted that an ICP registration algorithm could be applied to create a 3D point cloud from the scan data and to also compute rotation and translation of the ToF camera, supplementing the use of position encoders. To form a complete system, the ToF camera would require development, including adaptors, encoders, and orientation sensors, along with design of required electronic circuits.

PRELIMINARY TESTING AND RESULTS

Experimental Setup

This testing aims to demonstrate the capabilities and limitations of all the sensors within the underground cavity application at Cigar Lake. It also provides a baseline for the interpretation of data obtained from any of the systems during production. Since the shape, size, and target reflectivity of the cavity have an effect on the sensor performance, a testing space was designed to reflect the properties and size of a cavity as closely as possible. A hexagon shaped wooden enclosure was built with wall to wall distances varying from 4.2 m to 5.0 m. It was postulated that a wall shape similar to a cavity could be constructed with stucco. Diamond mesh was manipulated to cover the surface of the walls and a stucco base was applied. To finish, Cigar Lake core samples were examined and used to choose colours for stucco finish on the walls. The uranium ore is very strong and likely to protrude further than the surrounding, softer rock, when jetting is conducted. The high grade ore is also pitch black and for this reason, the greatest portrustions on the test cavity walls were painted black.

The main testing included baseline data acquisition, evaluation of the accuracy within a closed space on an uneven surface composed of various surface reflectivities, the effect of fog and water on the accuracy of range data, and object detection of freeze pipes. Additionally, the quality of the data obtained, the time in which it can be acquired, the associated cost, and the operator's ability to interpret the results will all play a role in evaluating which sensor is best suited for the interim and post cavity surveys.

Figure 2 – Left: Inside Cigar Lake cavity with freeze pipes, Middle: Test cavity construction, Right: Completed test cavity with SwissRanger and Senix mounted on Celestron Tripod in center

Data and Analysis

<u>MDL MKIII Cavity Auto-Scanning Laser System</u>

Before beginning the series of various experiments, it was important to acquire a set of baseline data from the C-ALS. The C-ALS is accompanied with package software that allows for several options in the acquisition process. In Figure 3 it can be seen how the interval angle affects the visual detail of the 3D plots. There is an obvious improvement in the visual information provided between a scan taken with a 5° interval to that of 1°. However, the difference between 1° and 0.5° appears less obvious, even though there are approximately twice as many data points and the scan will have taken twice as much time (Fig. 4). This will be a consideration for acquiring data in the field where time has a direct correlation with cost. At the mine, this data will be imported into Maptek software, using Isite for processing the scan data and Vulcan to access the cavity volume and compare against the mine plan.

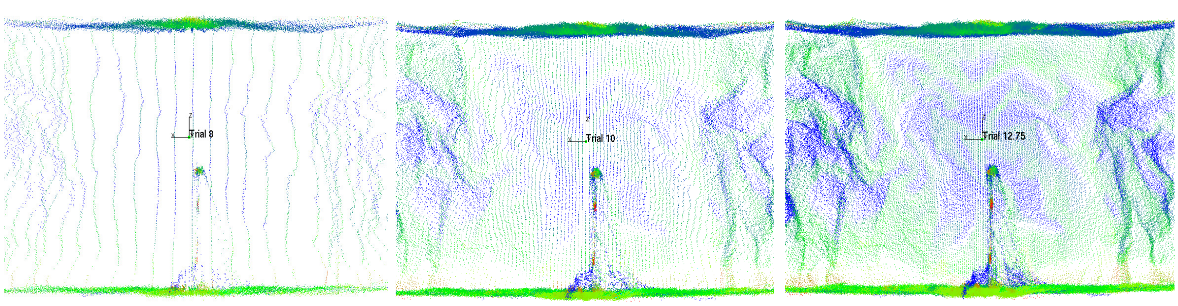

Figure 3 – Left to Right: C-ALS Vertical Scan 3D plots at acquisition intervals of 5°, 1°, and 0.5°. Colour scaled by signal strength.

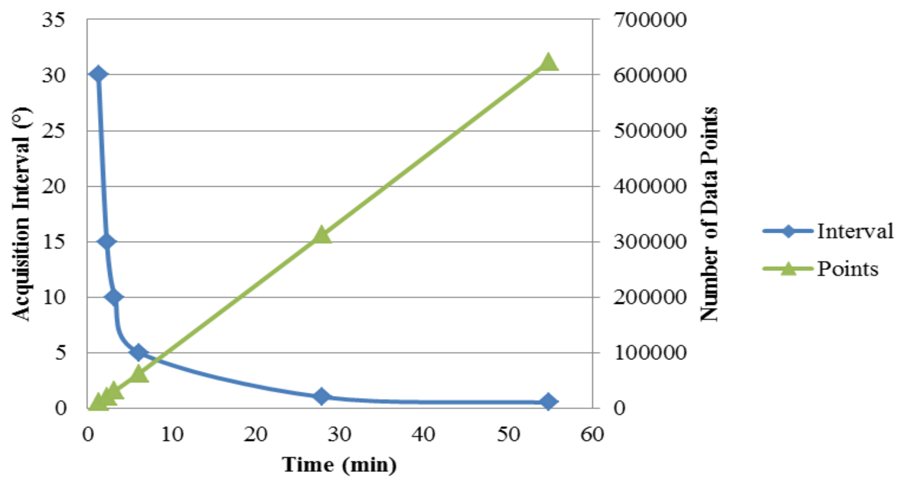

Figure 4 – C-ALS baseline vertical scan showing relationship between data acquisition interval, number of points obtained and, time for a complete scan

<u>MESA SwissRanger ToF Camera</u>

Since the SwissRanger ToF Camera is not part of a scanning system as the C-ALS is, a Celestron NexStar SE tripod was used to rotate the camera and output the angle of rotation. The ultrasonic sensor and SwissRanger were mounted to an adaptor designed by SRC as shown in Figure 2. A MATLAB script was written to rotate the tripod and to trigger data acquisition from both sensors. The 3D Cartesian coordinate data (*x*,*y*,*z*), along with a range, grayscale, and confidence map (Fig. 5) from the SwissRanger and a specified number of range values from the Senix sensor were acquired at each angle interval. In order to form a complete 3D point cloud from the 360° scan, it was first to determined whether the multiple frames of data could be aligned through registration, independently of the encoder angle. In this case, the registration itself could be used to find the rotation and translation of the device within the cavity.

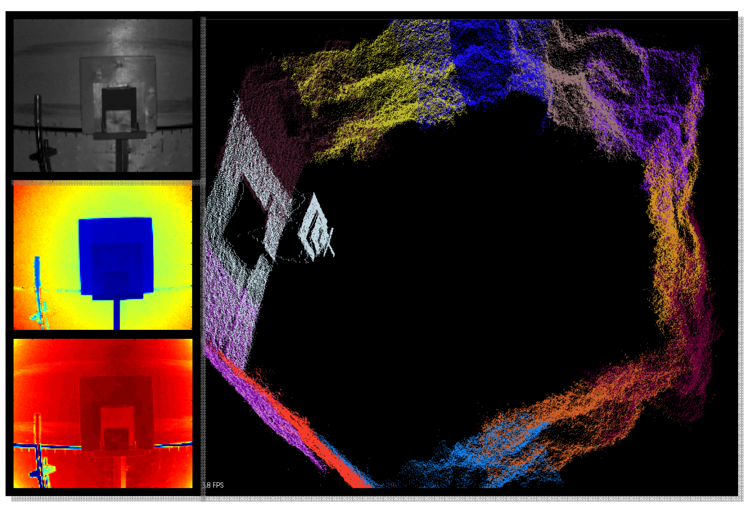

Figure 5 – Left: Basic image acquisition from SwissRanger using Matlab (Grayscale image, range image, and confidence map). Right: Point cloud data plotted by using PCL with tripod encoder angle.

To begin, example code for iterative closest point (ICP) registration from the Point Cloud Library (PCL) was modified; incorporating data taken inside the test cavity with the SwissRanger. PCL is a large scale, open project for 2D and 3D image and point cloud processing (Point Cloud Library (PCL), 2013). The ICP algorithm works by iteratively refining the estimated rotation and translation between two frames of point cloud data by minimizing the mean-square distance between their points (Paul J. Besl, 1992). It was expected that the success of registration would have some dependence on the amount of overlap between images, therefore, several sets of data were acquired using different angles of increment. For an average distance of 2.34 m between target and camera, an increase of rotation by 5° caused an increase in overlap by 10%. For initial trials, data acquired with a 10° increment and approximately 74% overlap between images was utilized.

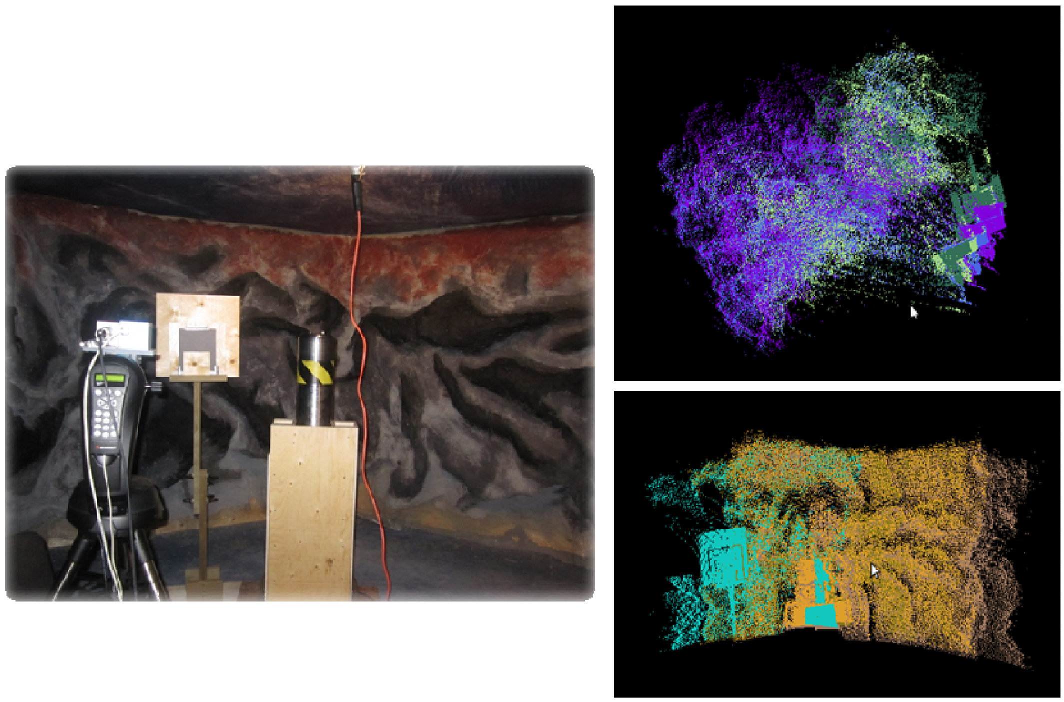

Figure 6 - PCL ICP Registration using five images, each acquired at an increment of 10°. Left: Test setup, Right Top: Unsuccessful registration attempt, Right Bottom: Partial success with registration

After several trials with the PCL ICP registration algorithm, and during the process of learning, it was found that some success could be had when distinctive objects, appearing in successive images were placed in the camera's field of view. Undesired convergence might occur when local point-to-point distances fall within the pre-set threshold. The ICP algorithm converges to a local minimum (Besl & McKay, 1992), so these objects ensured that the algorithm used sufficiently "rich" data. In a field situation, incorporating extra objects will not be possible so it is clear that more effort will be required to understand the potential robustness of the approach under various conditions. For example, the SwissRanger's confidence map could prove of use, since it is generated using a combination of distance and amplitude measurements and their temporal variations (MESA Imaging), and could suggest a strong starting point for matching. Filtering and feature extraction code is also available from the Point Cloud Library and will need to be further explored).

One obvious technique to achieve an improvement to the success of the registration process is by passing the known rotation of the images into the algorithm. Work is currently underway to observe the level of variance from the actual rotation that will cause the registration to fail (i.e., how good does the initial guess have to be?). The error in the rotation passed to the algorithm whereby the registration may still prove successful will be an important parameter for predicting realistic application within the field.

DISCUSSION

Preliminary comparisons can be made based solely on visual image evaluation and data acquisition time. Based on the specifications for each, it is already known that the SwissRanger is able to obtain data in a fraction of the time that the C-ALS is able to, and so, it comes as no surprise that the plot shown in Figure 7 from the SwissRanger is obtained in less than a second where, comparatively, the plot from the C-ALS is obtained within a few minutes. The image shows a stand supporting three square plywood boards, each approximately an inch apart. These boards can be visually resolved in the SwissRanger scatter plot but are arguably more difficult to resolve in the C-ALS plot. The accuracy of the data obtained from both has yet to be evaluated.

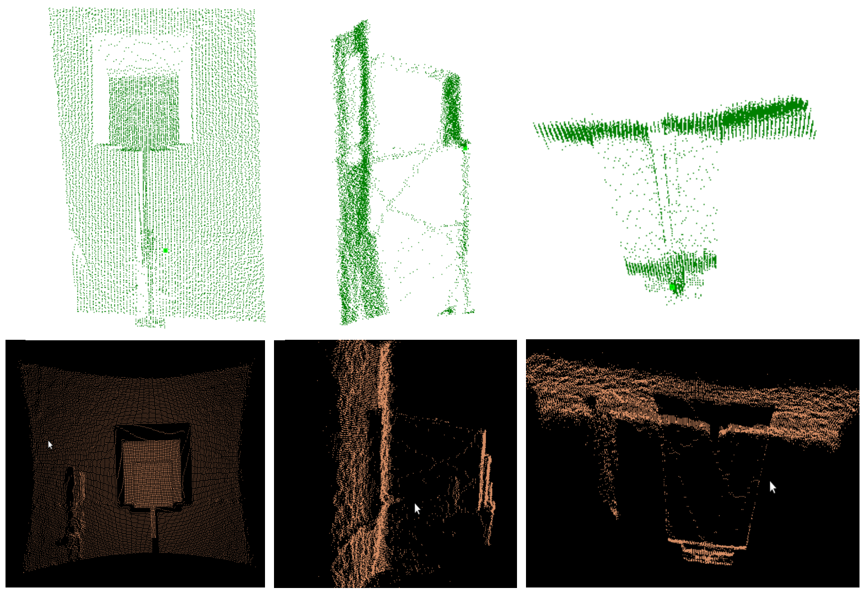

Figure 7 – Left to Right: Front, side, and top view of calibration stand, Top: 3D scatter plot of C-ALS Data from 0.5° vertical scan, Bottom: 3D scatter plot of single SwissRanger image using PCL viewer

In addition to the visual advantage of acquiring a dense data set in a short amount of time, an obvious benefit to JBS operators would be the grayscale image. The C-ALS is equipped with a video camera, but it is mounted at the end of the probe, not pointing in the same direction as the laser. This makes the association between the data acquired and the video image more difficult. The video is also a separate component, which increases the overall complexity of the system.

A clear advantage of the C-ALS is the application software that has already been developed. The data acquired from the SwissRanger has shown its potential, but much work has to be done in order to process the scan data and produce plots or images that are useful to JBS operators and for mine planning. It is anticipated that incorporating a known angular position as an initial 'guess' at alignment will provide an exceptionally better result in registration. The C-ALS uses encoder information to create 3D plots of the laser data and would not be benefitting from possible position correction gained from registration.

The data from the Senix ultrasonic sensor has not yet been evaluated. It is known that the sensor would be outperformed by the C-ALS and ToF camera within ideal conditions. The results of the Senix's performance within the test cavity in simulated cavity environments (ie. fog, water, etc.) and subsequently in the field will be the instance where its advantages could outweigh that of the optical signals.

CONCLUSIONS

Initial baseline data acquisition has demonstrated the potential for use of the SwissRanger ToF camera in a remote cavity scanning application at Cigar Lake. The high speed of data acquisition and the variety of images available for interpretation of data will be particularly useful for viewing inside the remote cavity. Further development is required to create a full 3D point cloud representation of the cavity using an encoder and registration algorithm, thereby correcting for potential error in rotation or translation.

Presently, the C-ALS would be the best choice for accurate cavity scanning because it is an easily available, complete system that incorporates deployment, pitch and roll sensors, and application specific software. If the ToF camera is shown to have comparable or even better performance in the extreme cavity conditions, the cost of further development to incorporate a ToF camera in a cavity scanning system may prove to be cost effective. This is the purpose for further research and analysis of data acquired under controlled conditions in the test cavity and later, if viable, in field at Cigar Lake.

REFERENCES

Measurement Devices Limited (MDL). (2013). Retrieved from www.mdl-laser.com

Besl, P. J., & McKay, N. D. (1992). A Method for Registration of 3-D Shapes. *IEEE*, 239-256.

Cameco Corp. (2010). *NI 43-101 Technical Report - Cigar Lake Project.* Retrieved from http://www.cameco.com/mining/cigar_lake/

Foix, S., Alenya, G., & Torras, C. (2011). Lock-in Time-of-Flight (ToF) Cameras: A Survey. *IEEE SENSORS JOURNAL*, 1917-1926.

Hedlund, T. (2010). *Registration of multiple ToF camera point clouds.* Umea University, Department of Physics.

Magnusson, M. (2006). *3D Scan Matching for Mobile Robots with Application to Mine Mapping.* Orebro University, Department of Technology.

MESA Imaging. (n.d.). *SR4000 User Manual Version 2.0.* Retrieved March 30, 2012, from http://www.mesa-imaging.ch/prodview4k.php

Oggier, T., Kaufmann, R., Lehmann, M., Metzler, P., Lang, G., Schweizer, M., et al. (n.d.). *3D-Imaging in Real-Time with Miniaturized Optical Range Camera.* Retrieved April 15, 2012, from http://mesa-imaging.ch/publications.php

PCL. (n.d.). *How to incrementally register pairs of clouds.* Retrieved July 3, 2012, from http://pointclouds.org/documentation/tutorials/pairwise_incremental_registration.php

PCL. (n.d.). *The PCL Registration API.* Retrieved July 3, 2012, from http://pointclouds.org/documentation/tutorials/registration_api.php

Point Cloud Library (PCL). (2013). Retrieved from http://pointclouds.org/

SRC. (2005). *Review of the Cavity Survey System, Post Survey Tool and Casing Hole Survey System.* Saskatchewan Research Council, Development Engineering. Saskatoon: SRC Publication No. 11265-IC05.

SRC. (2006). *CVSS Ultrasonic Sensor Report.* Saskatchewan Research Council , Development Engineering. Saskatoon: SRC Publication No. 11265-1C06.

Wacker, M. (2001). *2000 Jet Boring Systems Test - Final Report.* Cigar Lake Mining Corporation.