Development of Inspection and Surveying Tool for Vertical Mining Openings and Shafts

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Key words: vertical openings, video inspection, laser scanning, mapping

SUMMARY

Underground mining operations create many vertical (or near vertical) shafts to allow movement of rock (passage of ore) or ventilation between different levels within a mine. In most cases these shafts are not easily and safely accessible. A reliable and safe method of shaft monitoring is required. The inspection and surveying system, which is presently under development at the Western Australian School of Mines (Curtin University), should provide such capacity and allow for a corrective action, if required. The unit's design is based on standard, off the shelf and low cost, components merged with smart programming and advanced communication systems. The tool acquires digital images, utilising its forward and side view cameras, and combines them with pod motion data (provided by the on-board inertial system) when lowered along a shaft or ore pass. An extension of the inspection pod with a laser scanner allows it to collect metric data of the inspected vertical openings. All data is transmitted to the control station. The monitoring results are processed and compared with previous surveys and any changes are detected. The project is at the advanced stage of development with all components selected and assembled. This paper presents issues that had to be resolved during the development of the system, as well as the results of initial survey and data processing.

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1. INTRODUCTION

Underground mining operations frequently require vertical (or near vertical) shafts to allow movement of rock (passage of ore) and passages of air (ventilation) between different levels within a mine and the surface. In most cases these shafts are not easily accessible for inspection; however, for operational reasons a safe and reliable method of inspection is required. The VOIS (Vertical Opening Inspection System) is intended to provide this capacity and form the basis of an inspection and survey platform for vertical shafts. The collected visual and metric data can provide the necessary information required for stability and safety assessment, as well as, for planning of eventual reconstruction (Logan et al. 1993, 321). With the close involvement of industry, providing design input, the research and development project yielded a platform, to allow the inspection and survey of vertical openings and shafts in the mining environment.

Conceptually a platform assembly for inspection process are quite simple. A platform with motion sensing (IMU), stabilisation (gyro), video and distance sensing devices (cameras and laser scanner) is lowered into a vertical shaft on a cable and data is collected as it is lowered, Figure 1.

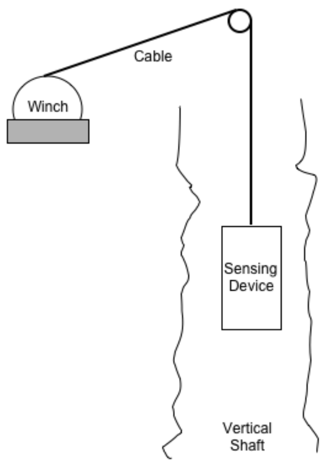

Figure 1: Vertical shaft inspection concept

However, during development of such platform several design issues were discovered that had to be resolved before a successful working prototype could be assembled.
Three application studies are presented with data collected by the VOIS prototype. Ultimately, the platform will be offered to the mining industry as an integrated inspection and

survey tool that provides quantitative engineering data and allows personnel to effectively manage the conditions of vertical openings in the underground mining environment.

2. SYSTEM DEVELOPMENT PROCESS

An iterative development strategy coupled with readily available component selection COTS (Commercial off-the-shelf) was adopted during the design. Complete OEM (Original Engineering Manufacturer) assemblies were selected to meet the requirement of each sub system, such as inertial gyro stabilisation, IMU (Inertial Measurement Unit), DSL (Digital Subscriber Line) data modems, and Fire Wire video cameras. Each sub system was linked together using inexpensive microprocessors communicating with each other using standardised communication interfaces, such as RS-232, USB (Universal Serial Bus) and Ethernet. Extensive use of 3D modelling was employed to visualise prototypes before construction. The iterative design process allowed test results to feed back into the design for further improvements as development progressed, Figure 2.

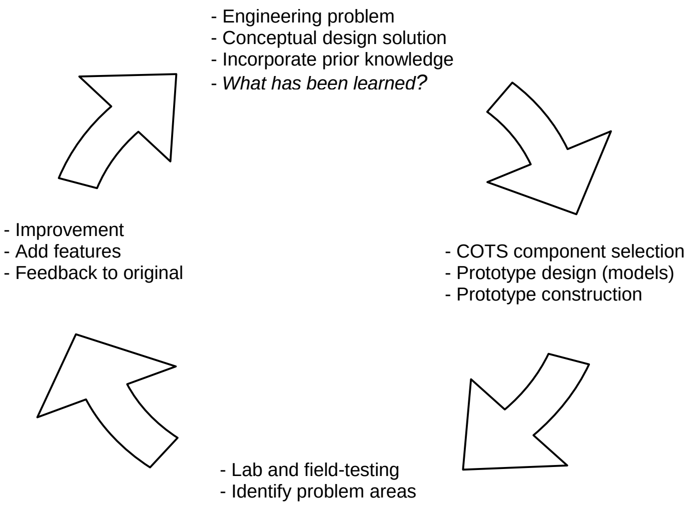

Figure 2: Design cycle

3. CURRENT SYSTEM COMPONENTS

The VOIS is comprised of two major components; 1) the deployment system, and 2) the pod or survey tool itself. The deployment system consists of a winch and a hydraulic crane mounted to a modified light vehicle. The pod contains stabilisation and sensing devices for video capture and laser scanning.

3.1 Deployment System

A commercial off the shelf wire line winch was selected with suitable specifications to suit the mass of the pod about 50 kg. The winch was modified to include an intelligent microprocessor controlled counter for indication of depth, slip rings to allow electrical connections to the rotating cable drum, data communication, control pendant for winch drive speed and cable payout. One kilometre of four (4) conductor steel armoured wire line was spooled onto the winch with a cable drum total capacity of 2 kilometres. A function diagram of the winch components is shown in Figure 3.

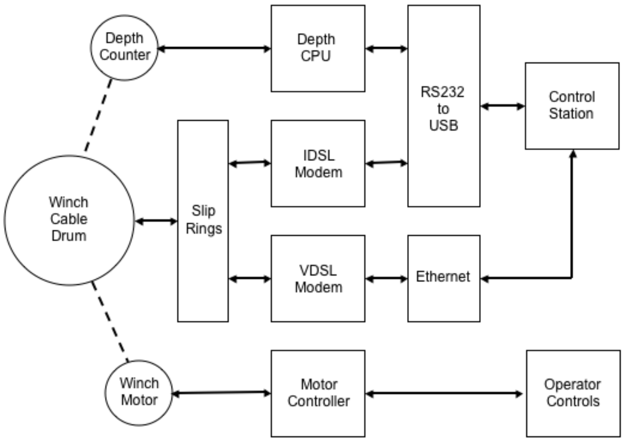

Figure 3: Winch block diagram

A commercial hydraulic crane was also acquired for positioning the pod during deployment. The winch and crane assembly was mounted on a modified Toyota C100 4WD vehicle to enable access to remote mining operations. A photograph of the survey vehicle with crane and pod deployed down a test shaft is shown in Figure 4.

Figure 4: Deployment system

3.2 Pod Component Hardware

The pod system is divided into four major components, namely:

- Data Communications and Power Control
- Gyro Stabilisation and Motion Data Collection System
- Digital Video Capture and Control
- Laser Scan Data Capture and Control

Each pod component utilises several embedded sub processors to provided distributed control of the various functions as shown in Figure 5.

Distributed processing allowed rapid development of the pod component systems independent of one another. Standardised communications links (Fire Wire, RS232, USB, and Ethernet) were leveraged to link the sub processors together into a fully functional system.

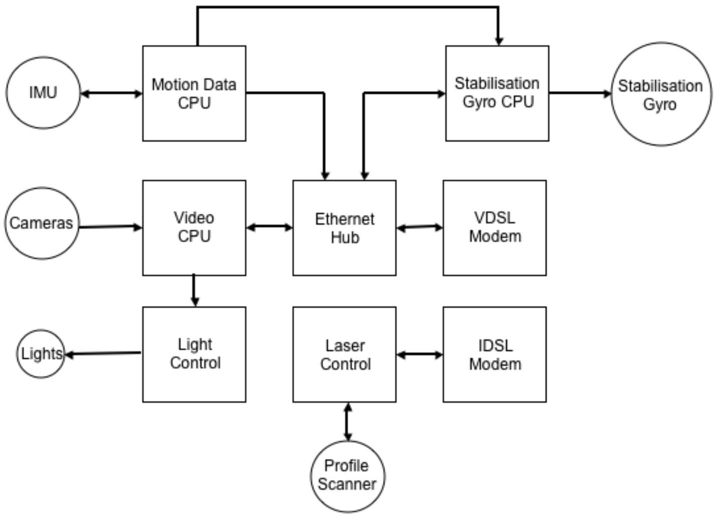

Figure 5: Pod component sub processors

3.3 Gyro Stabilisation and Motion Data Collection

The Z-axis rotation of the pod is stabilised using an inertial spinning mass gyro used for film camera stabilisation. The commercial Kenyon-6 gyro is mounted in the centre of the pod. An ATMEL 16MHz 8-bit ATMEGA8535 control processor using Ethernet data communication is used to remotely “spin up” the gyro at the start of pod deployment.

Changes of pod orientation and X, Y-axes acceleration are provided by a Crossbow AHRS-300CA (Attitude Heading Reference System) mounted directly above the stabilisation gyro. The AHRS is connected via RS232 to a Vortex86 166 MHz industrial single board computer, which calculates pod azimuth and accelerations. The calculated data is streamed to surface control computer using TCP/IP via Ethernet to VDSL link over the wire line.

3.4 Digital Video Capture and Control

Video images are collected using five side cameras mounted at 72° intervals to cover the full 360° view. Each side looking camera has an 85° wide-angle lens to ensure overlap of collected images. A single camera is mounted at the bottom looking directly down. This camera is primarily used for navigation and observation of any obstructions, when lowering the pod into a vertical shaft. The camera assembly is mounted in the lower portion of the pod and connected via a Fire Wire bus to a low power PC104 computer utilising an 800 MHz Transmeta Crusoe processor. Ten 20-watt halogen dichroic flood lamps provide illumination for side cameras. Front illumination is provided by four 5-watt high intensity LEDs (Light

Emitting Diodes) coupled with wide-angle lens assemblies. Images are captured to frame buffer using custom software on the PC104 computer. The PC104 computer incorporates a relay board that allows remote control of the halogen illumination from surface. A photograph of the pod's camera section is shown in Figure 6. From the top showing the PC104 computer (top centre), VDSL modem (top right), side halogen illumination deck (middle), camera deck (below), integrated laser scanner (bottom), and front LED illumination (just visible bottom). The camera section is protected by a steel guard.

Figure 6: Pod lower section

3.5 Laser Scan Data Capture and Control

Laser scanning is accomplished by the SICK LD-OEM unit capable of providing continuous 360° profile data streams. The, off the shelf scanner, is integrated into the bottom of the pod below the camera section as shown in Figure 6. Laser profile data is output during scanning at a rate of 115.2 kbs via an RS232 interface. Data is fed directly into an IDSL data link to the control computer. Laser profile data is output on surface as RS232 directly to the surface control computer via USB shown in Figure 3.

3.6 Data Communications and Power Control

Video metric and control data collected by the pod is transmitted to the control computer via the wire line suspension cable.

Captured video images are compressed to JPEG and sent to the winch, at the top of a shaft, as UDP packets via the Ethernet to VDSL (Very High Speed Digital Subscriber Line) modem, utilising a single pair of copper conductors in the wire line cable. A second VDSL modem on the winch provides a direct Ethernet connection to the control computer. Pod orientation azimuth and X, Y plane acceleration data is also sent via this Ethernet link to the control computer. Control signals for illumination, inertial motion, and power control are sent down to the pod from the control computer via Ethernet over the VDSL link.

Laser profile data is sent to the surface computer in serial RS232 format via an IDSL (ISDN over Digital Subscriber Line) modem using the second pair of copper conductors in the wire line. Laser control data from the control computer is sent down to the pod using the same data link.

Pod power is controlled from the winch control panel. The control voltage powers a latching relay in the pod allowing remote on/off control.

3.7 CONTROL SOFTWARE

3.7.1 Video Capture

The video capture and control software on the control computer communicates via TCP/IP with the PC104 computer in the pod. The surface interface allows control of individual camera frame capture rate, illumination, and recording to hard disk. Display of video from all six cameras is possible to allow an operator a 360° view of the vertical shaft while lowering the pod. A photograph of the video control software is shown in Figure 7.

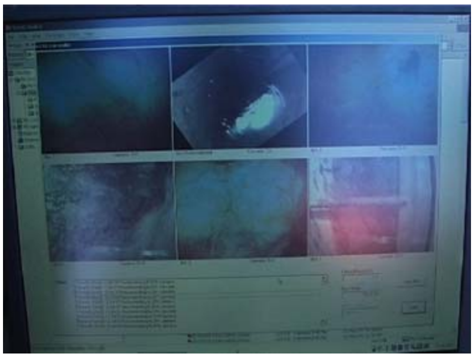

Figure 7: Video control interface

Video images from the pod can be displayed as view only. This mode is primarily used with the forward-looking camera to observe for any obstructions when lowering the pod. Captured JPEG images, saved to disk can, be post processed and constructed into movies.

3.7.2 Gyro Stabilisation and Laser Scanning

The scanner and gyro stabilisation software uses direct RS-232 serial links and TCP/IP over Ethernet to control these systems in the pod. Laser command functions allow direct control over the pod laser scanner. They allow for start or stop of the scanning system, get and set laser scan configuration values, and system reset. A visual indication of the laser profile data is displayed in real time while scanning with a polar sweep graph including zoom function and automatic orientation correction of the profile orientation.

Pod orientation data is visually displayed in real time using a simple graduated degree dial gauge along with relative accelerations of the pod in the X, Y directions of IMU.

Depth is updated in real time, while raising or lowering the pod, using a large format digital display. Depth data is read from the intelligent depth encoder, located on the winch, to give an operator an indication of the pods deployment depth.

Raw information from the laser scanner, IMU (AHRS) and depth encoder is also included as diagnostic information for the operator.

Recording functions can be enabled to spool the laser scanner and/or IMU data to disk for later post-processing. Saved raw data can be played back and converted to human readable text format using the control panel playback functions. A “screen shot” of the control interface is shown in Figure 8.

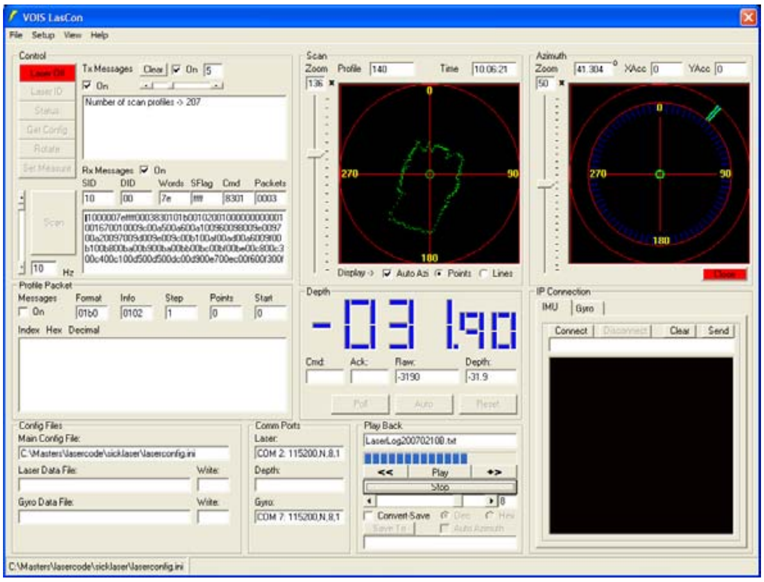

Figure 8: Pod laser and IMU control panel

4. SYSTEM DEVELOPMENT

During the testing phases of the project several design issues were encountered. These issues were resolved using the iterative design approach to arrive at a final working prototype described in the previous section. The initial stage of the system development was carried out by CSIRO – Exploration & Mining in Brisbane. During this stage the video capture and winch deployment subsystems where developed.

4.1 Suspension and Stabilisation

A 9.8mm diameter polyurethane sheath underwater camera cable was initially used for pod suspension. During fields trials two major issues were encountered with this cable. The 9.8 mm outer diameter only allowed 300 meters of cable to be spooled onto the winch drum, restricting the vertical deployment range of the suspended pod. The second issue of more concern was that the polyurethane outer sheath of the cable had significant amount of elasticity causing the pod to spin rapidly when raised or lowered. The rapid rotation rendered the captured video images not useable.

These two issues were addressed by replacing the polyurethane cable with a four conductor, 4.72mm diameter, steel armoured DATALINE® logging cable from the Rochester Corporation. The 4.72mm diameter allowed up to 2 km of cable to be spooled onto the winch drum; however, due to supply constraints only 1 km of cable was acquired. The DATALINE® counter wound inner and outer “gipps” wire sheaths address the second issues by counteracting the cable torsional forces reducing pod rotation when raising or lower, but not stopping the rotation entirely.

To stop pod rotation during deployment a simple pulley suspension system was constructed to allow two suspension points of the pod and to maintain its fixed orientation as it is lowered into a vertical shaft. Initial lab tests over short distances showed that the pulley system maintained pod orientation. A photograph of the pulley system during lab tests is shown in Figure 9. However, field deployment revealed that the pulley system maintained the pod orientation up to a deployment depth of approximately 60 meters, beyond which the torsional force in the cable caused the whole pod system to rotate twisting the cable together as shown in Figure 9.

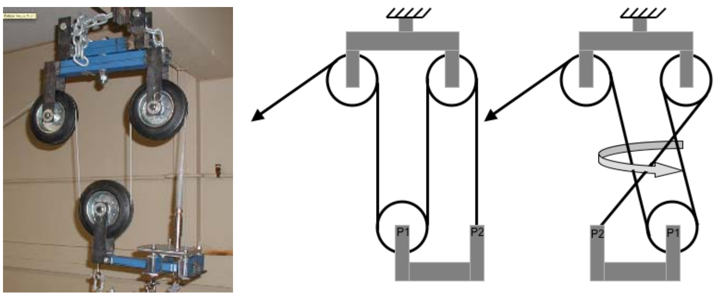

Figure 9: Pulley system and cable twisting

Unsatisfactory field trials of the pulley system prompted a novel approach to further stabilise the pod during deployment using a commercial movie (film) camera stabilisation gyro from Kenyon Laboratories. When spun up to operating speed the Kenyon-6 gyro provided resistance torque to rotational motion perpendicular to its spin axis. The gyro was mounted centrally in the pod with its spin axis perpendicular to the pod Z-axis. Static mounting of the stabilisation gyro did not stop pod rotation, when raised or lowered, but significantly damped rotation range and rate around its Z-axis.

To further control (counteract) pod rotation the gyro was mounted on an active platform allowing for its rotation in relation to the rest of the pod. In this configuration the gyro driven by a step motor rotating a stage controlled by the IMU and feedback processor to dynamically counteract pod rotation. Once "spun up" the gyro azimuth is remotely stepped incrementally left or right in a manual fashion. When the gyro is spinning and producing a resistance torque the stepping rotation causes the pod to rotate about its Z-axis while the gyro remains stationary. Reading azimuth from the IMU (AHRS) a feedback loop applies corrections by rotating the entire Kenyon-6 spin axis. This forms the basis of an active stabilisation control system and allows the pod to track an azimuth heading as it is deployed into a vertical shaft.

Lab tests produced promising results, but the active stabilisation system requires further development to produce a fully stable control loop.

4.2 Data Communications

The pod sensors produce large amounts of data. A suitable high bandwidth communications method is required. The data communications system should be capable of high speeds and also able to cope with transmission in an aggressive environment (electrical noise and long cable lengths). In addition the communication system required a standard end user data interface, such as Ethernet. Various DSL technologies were tested with the steel wire line. ADSL and SHDSL (Asymmetric/Symmetrical Digital Subscriber Line) were found to be unsuitable. VDSL was tested and proved to be successful at transmitting high-speed data at 4.3 Mbps over the wire line cable using two of the four available copper conductors. A VDSL modem was selected with an Ethernet user interface to provide a standard data interface end to end. Lab testing revealed that the non-deterministic nature of Ethernet was suitable only for non-time critical video and gyro data traffic, but unsuitable for time critical laser profile data streams. Time critical data from the laser scanner required a synchronous data communications system to ensure a deterministic data link. The DSL technology proved capable of handling the aggressive transmission environment and another DSL variant was tested, ISDL (ISDN over DSL), which provided a synchronous deterministic data connection with standard RS232 end point user connections. The ISDL modem set was successfully tested on the wire line using the second two copper conductors and co-existing with the VDSL modem using the adjacent conductors.

4.3 Video Capture

Design related to video capture centred on two issues, optical properties, and frame buffer capture timing.

A Perspex shroud was employed to protect the cameras and lights during deployment and provide a suitable transparent medium. However, the Perspex was subject to "crazing", resulting in numerous internal stress cracks that obstructed the view of the cameras and rendered hazy images. The solution was to simply cut holes in the Perspex for the camera lenses to provide unobstructed view. To protect the cameras from external environment the holes were later shielded with transparency film.

Additional optical issues resulted from the use of aluminium plating as a support structure for the cameras. The reflective surface of the aluminium mounting plates caused a significant amount back reflected light into the cameras causing glare in the lenses. This issue was address by painting all reflective aluminium surfaces around the cameras with flat black paint.

Camera frame buffer timing was found to be a problem when the video CPU was capturing all six cameras simultaneously. The problem manifested itself as frame jitter between cameras and captured frames would drop in and out of sync with one another.

4.4 Illumination

The halogen lamp illumination accounted for 80% of the overall power consumption of the pod. In addition they generated a significant amount of heat during extended operating times. The excessive heat eventually damaged some electrical components causing a fire inside the pod. This prompted the addition of heat shielding of electrical components and wiring in the vicinity of the halogen lighting. Investigation was undertaken to find a more suitable light source. Front illumination originally provided by two 10-watt halogen dichroic flood lamps were replaced with four 5-watt high intensity LEDs (Light Emitting Diodes) coupled with wide flood lenses. The LED illumination significantly reduced power consumption and heat, however, at present the halogen side illumination is still installed. It is to be replaced at a later time with LED illumination, as it requires a significant amount of mechanical redesign of the pod illumination and camera section.

4.5 Power Supply

Power in the pod is supplied via two onboard 12 V 14 AH, high capacity, sealed, lead acid batteries. Onboard batteries are required due to the large current demand imposed by the halogen illumination. A central power control system was also required, so each sub system could be shut down when its operation is not required, to conserve stored energy. Photograph shown in Figure 10 details the pod lead acid batteries and the power controller.

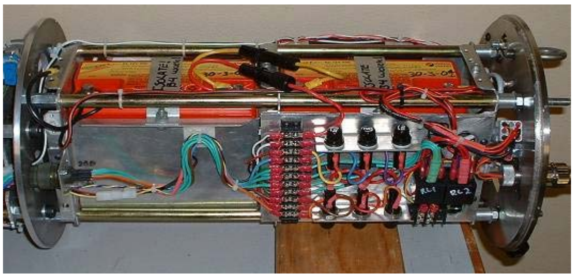

Figure 10: Pod primary batteries and power controller

Reduction of overall power consumption is an ongoing development as the large current requirement demanding large batteries accounts for one third of the total pod length of 1.3 meters and one half of the pod weight of 55 kilograms.

4.6 Laser Scanning

During the design cycle a suitable profile laser scanner as reviewed by Staiger (2003), Fröhlich and Mettenleiter (2004) could not be sourced as an OEM component. An available TOF (Time of Flight) Acuity Research 4000-LIR laser distance measurement unit was selected and a rotating mirror assembly was built to obtain a unobstructed 360° scan profile. During the design process 3D models were used to conceptualise the rotating mirror assembly. A tube driven by a brush less DC motor with an end cap mirror was constructed based on the 3D model as shown in Figure 11.

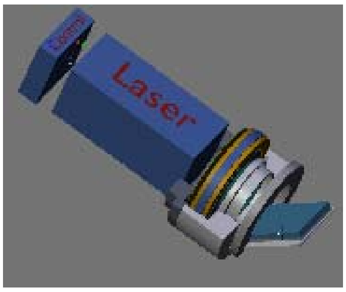

Figure 11: Model of laser and rotating mirror assembly

The Acuity Research 4000-LIR laser mounted in line with a motor driven mirror allowing it to scan a full 360° profile. To determine angular position of the mirror an optical encoder wheel was constructed. The optical pattern on the wheel was created using postscript code and simply printed onto transparency sheet. A 600 dpi laser printer provided sufficient resolution to create an encoder wheel with an angular resolution of 1 in 1000.

During the final phases of the laser scanner development OEM vendors were searched periodically in an attempt to locate a COTS scanner as part of the iterative design process. The SICK LD-OEM profile laser scanner was identified as fulfilling the design requirements and obtained. The SICK LD-OEM scanner employed the same scanning technique as our original prototype scanner, but the SICK unit had the advantage of being a completed production unit. Work on our own laser scanner ceased and the design focus shifted onto integration of the SICK scanner. A photograph of the prototype scanner alongside the commercial SICK LD-OEM scanner is shown in Figure 12.

Figure 12: “In house” prototype (left) and commercial scanner (right)

5. CASE STUDIES

Three case studies, presented in this paper, show deployment of the VOIS system for inspection and survey of vertical shafts located in three separate mining operations.

5.1 Video Inspection of a Ventilation Shaft

A mine site located in Western Australia had large ingress of water into a 300-metre upcast ventilation shaft. The shaft had a steel lining over the first 100 meters. The water ingress was causing significant problems for the surface ventilation fan. The water being hyper saline was corroding fan components. The source of the water ingress needed to be determined so corrective action could be taken. A visual inspection was carried out to find the source of the water ingress. Digital images captured on the side view cameras are shown from selected depths as the pod was lowered from surface into the ventilation rise. Figure 13 and 14 present a panoramic image strip.

Figure 13: Ventilation shaft 100 meters depth

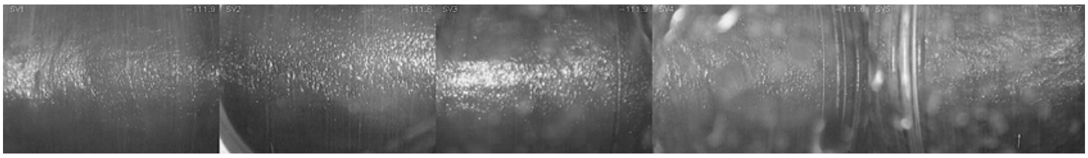

Figure 14: Ventilation shaft 110 meters depth

5.2 Ore Pass Wear

A mining operation located in Indonesia with several raised bored ore passes of over 600 meter depth required a safe and economic method of visually inspecting their condition. A video inspection was carried out to assess wear and potential for instability. Panoramic 360° digital images of a selected ore pass are shown. The walls are polished surfaces and geological structure can be seen in panoramic image strip, Figure 15.

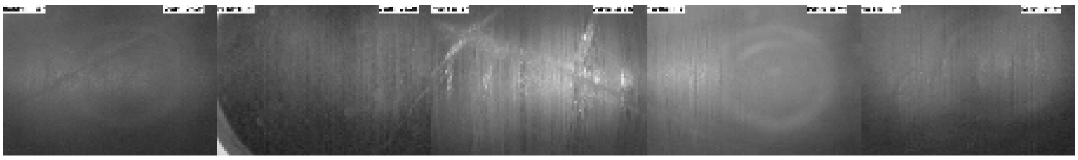

Figure 15: Ore pass walls

5.3 Ore Pass Laser Survey

A large nickel mining operation located in remote Western Australia started to experience anomalous behaviour of three production ore passes. Drawn material tonnes began to exceed the original designed capacity, which led to cause for concern. A laser survey was required to determine the detailed shapes and condition of the ore passes.

The resultant laser scan data is shown as scan strings and rendered solids in Figures 16a and b respectively.

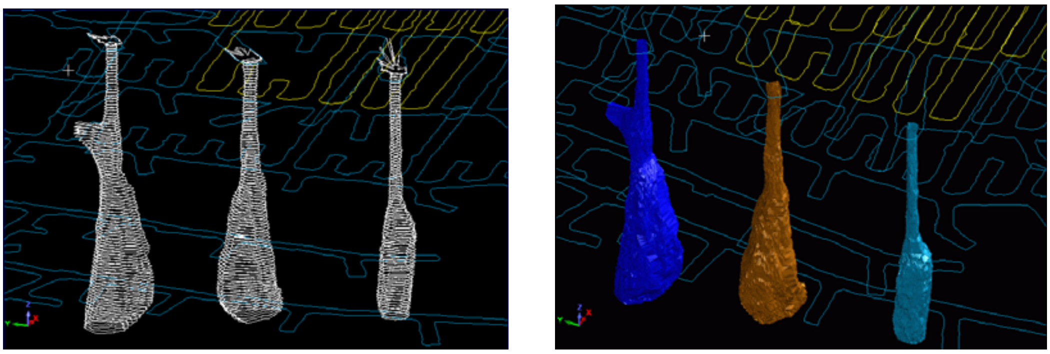

Figure 16: Ore Pass a) Wire Frame and b) Rendered Solids

The rendered solids clearly indicate that the left and centre passes had undergone significant shape change as compared the right ore pass, which most closely matched the original design.

6. FURTHER SYSTEM DEVELOPMENT

Arriving at a successful working prototype realised the goal of producing an inspection and survey tool for vertical shafts and openings. However, the design cycle will continue taking “what has been learned” to optimise the design.

Final optimisation development will include:

- Selection of smaller OEM versions of sub systems reducing pod dimensions and mass,
- Reduction of power consumption enabling smaller batteries,
- Integration of surface video capture and laser control software into single package,
- Simplification of mechanical assembly to reduce number of components,
- Utilisation of data for construction of virtual reality modems.

Completion of the above will produce a final production version of the inspection and survey tool for vertical shafts and ore passes.

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BIOGRAPHICAL NOTES

Andrew P Jarosz, MEng, PhD (Krakow, Poland), received his undergraduate and graduate education (1968-73) at the University of Mining and Metallurgy (AGH) in Cracow, Poland, and graduated with a Diploma in Mine Surveying. His early professional career includes work for the University of Mining and Metallurgy (AGH) in Cracow (1973-79) and for Central Mining Institute in Katowice, Poland, (1979-83). Over 1980-81 he was actively involved in creation of Free Trade Union - Solidarity. He was forced to leave his country in 1983. With his family he moved to USA and most time (1984-90) worked as a Research Associate at the Department of Mining and Minerals Engineering, Virginia Polytechnic Institute and State University in Blacksburg, Virginia. In 1990 after receiving offer from the University of Witwatersrand, Johannesburg, he joined the staff of the Department of Mining Engineering as a Senior Lecturer. From 1996 Dr Jarosz is a Senior Lecturer at the Western Australian School of Mines (Curtin University) in Kalgoorlie. He was Chair of Mine Surveying Program and Head of Mining Engineering and Mine Surveying at WASM. Dr Jarosz's research interest are in areas of mine design and optimisation, deformation monitoring and prediction, practical application of ground control principles in mining, mine surveying with special emphasis on utilisation of laser scanners and remote sensing technology. He has authored and co-authored many technical papers on these subjects.

James Langdon, holds a BESc (Electrical 1988-92) from the University of Western Ontario, Canada. Early engineering work at the Geomechanics Research Centre Sudbury, Ontario (1992-95) includes seismic monitoring and data communications systems in mines. Relocated to South Africa as a Senior Systems Analyst at ISS International specialising in seismic monitoring systems for mining (1995-98) and later appointed General Manager of ISS Pacific Pty Ltd (1998-2002) and moved to Kalgoorlie, Western Australia. Departing ISS he joined Gold Fields, St. Ives Gold information technology group (2002-05) primarily involved with mining telecommunications systems. 2006 saw his departure from Gold Fields to enrol as a full time Masters student at the Western Australia School of Mines, Kalgoorlie, Western Australia (2006 to present). He maintains an active involvement in information technology, electronic design and hardware development as an independent consultant.

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